THE COUPLING COMPENSATION AND MEASUREMENT IN THE INTERACTION REGION OF BEPCII

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Abstract

The detector solenoid field in the BEPCII interaction region will be compensated by six anti-solenoids, which are located nearby the interaction point. Skew quadrupoles are adopted for the global coupling compensation. The coupling compensation scheme and the method to tune and measure the x-y coupling at the interaction point will be introduced in detail.

COUPLING COMPENSATION SCHEME

The BESIII detector solenoid has maximum field strength of 1.0T over an effective length of ±1.8m around the interaction point (IP) where the particle motion between the horizontal and vertical planes will be coupled. The lattice functions, the vertical emmittance and the tilt angle of beam are strongly related to the coupling parameters. Therefore, without the dedicated coupling compensation it is impossible to meet higher luminosity. According to the requirements of high energy physics, BEPCII will be operated at the energy range from 1.0GeV to 2.1GeV, so the compensation system should be powerful enough to work perfectly for particles within the momentum range. For this purpose an anti-solenoid system has been designed in the superconducting magnet package to realize the local compensation of x-y coupling effects in the interaction region (IR). This system consists of three anti-solenoids AS1, AS2 and AS3 and a skew quadrupole inside the superconducting cryostat. AS1 locates between the IP and the superconducting quadrupole (SCQ) which acts as the first vertical focusing quadrupole. AS2 and the skew quadrupole overlap SCQ, while AS3 locates after SCQ. They are all dedicated to the compensation of the detector fields along the beam line for both e+ and e- rings which have the same beam energy. The local compensation layout of BEPCII and wiring schematic diagram are shown in Fig. 1.

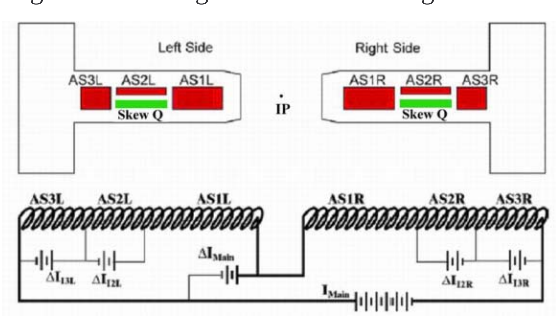

Figure 1: The local coupling compensation layout of BEPCII and wiring schematic diagram.

With this compensation scheme, the integral field ∫Bzds between the IP and SCQ is zero. The longitudinal field over SCQ is nearly zero and the integral field ∫Bzds between SCQ and the first horizontal focusing quadrupole is zero too. As well known the compensation of longitudinal field within SCQ region is a key for higher luminosity. The skew quadrupole which overlaps SCQ can make fine tuning of longitudinal field over the SCQ region instead of the mechanical rotation method. AS2 and AS3, which have their own independent trim circuits to allow fine tuning of the anti-solenoid compensation scheme, are in series with AS1.

Fig. 2 shows the distribution of the axial combination magnetic field Bz along the axis of BESIII detector after compensation simulated by OPERA-2D code.

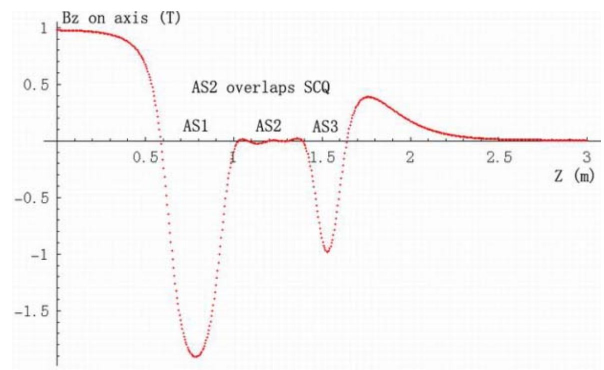

Figure 2: The distribution of the axial combination magnetic field along the axis of the BESIII detector.

Since the anti-solenoids AS1, AS2, AS3 and the skew quadrupole are the common elements for both e+ and e- rings, it is necessary to add some independent variables for the coupling adjustment of one ring with the coupling of the other ring unchanged. Due to the limitation of free space, we arrange four skew quadrupoles only for each ring, which are distributed in the interaction region, injection regions and RF region respectively for the further fine tuning of coupling. The horizontal dispersion in those regions is free so that the changes of the vertical dispersion and its slope can be neglected during the coupling adjustment. The global coupling parameter and the beam tile angle at the IP of each ring, which are induced by solenoid field, the beam vertical orbit distortion inside the sextupoles and the parasitic x-y coupling due to machine errors, can be compensated by tuning the strength of the skew quadrupoles and anti-solenoids.

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METHOD AND ALGORITHM OF COUPLING MEASUREMENT AT THE IP

The tile angle of beam strongly relates to the coupling parameters which have measurable effect on the luminosity. Therefore, it is important to measure and control the coupling parameters accurately at the IP. For the BEPCII design proposal, a shaker and two sets of turn-by-turn BPM's will be adopted to measure the coupling parameters.

While the beam is coherently excited by the shaker at the frequency of horizontal tune in the horizontal or vertical plane, a saturated state will be reached with the balance between sympathetic vibration and the radiation damping after a few damping times. The betatron oscillations can be measured by turn-by-turn BPM's which locate near IR and use same trigger signal for the revolution. A harmonic analysis will be performed to extract the x-y coupling parameters at the IP from the detected betatron oscillations[1].

Consider only the linear transverse motion in a storage ring. It has been shown by Edwards and Teng[2] that the one-turn transfer matrix in a periodical and symplectic system can be decoupled by a new transformation

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

Here, T is a 4×4 one-turn transfer matrix in the physical system and $M_{u,v}$ are 2×2 one-turn transfer matrices in the normal system. The normal mode coordinate $U = (u, p_u, v, p_v)$ relate to the physical coordinate $X = (x, p_x, y, p_y)$ via

$$U = C \cdot X. \qquad (2)$$

The 4×4 matrix C is defined by

$$C = \begin{pmatrix} \mu\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} . R^T . \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \\ R & \mu\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{pmatrix}, \qquad (3)$$

where the sub 2×2 matrices R is defined as

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

The relation between μ and R is $\mu^2 + \det R = 1$. We refer to r_1, r_2, r_3 and r_4 as the x-y coupling parameters. If there is no coupling, the four coupling parameters are zero. The coupling matrix C is defined at each position along the orbit.

Since $M_{u,v}$ are symplectic matrices, they can be parameterized with the well-known Courant-Snyder parameters

$$M_{u,v} = \begin{pmatrix} \cos(2\pi\nu_{u,v}) + \alpha_{u,v}\sin(2\pi\nu_{u,v}) & \beta_{u,v}\sin(2\pi\nu_{u,v}) \\ -\gamma_{u,v}\sin(2\pi\nu_{u,v}) & \cos(2\pi\nu_{u,v}) - \alpha_{u,v}\sin(2\pi\nu_{u,v}) \end{pmatrix}, \qquad (5)$$

where ν_i is the frequency of the eigenmode. It can be measured in unit of revolution frequency.

Assuming that the beam oscillation is excited coherently by a horizontal shaker source, the particle motion in the physical coordinate can be obtained from Eq. (2):

$$\begin{aligned} \mu\, y &= -r_1\, x - r_2\, p_x \\ \mu\, p_y &= -r_3\, x - r_4\, p_x \end{aligned} \qquad (6)$$

The four x-y coupling parameters r_1, r_2, r_3 and r_4 can be extracted from the physical beam oscillations with consecutive turns after transforming the Eq. (6) into series and trigonometric function format.

$$\begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix} = -\mu \begin{pmatrix} C_y^u & S_y^u \\ C_{p_y}^u & S_{p_y}^u \end{pmatrix} \begin{pmatrix} C_x^u & S_x^u \\ C_{p_x}^u & S_{p_x}^u \end{pmatrix}^{-1} \qquad (7)$$

where

$$\begin{aligned} C_w^u &= \sum_n w(n)\cos(2\pi\nu_u n) \\ S_w^u &= \sum_n w(n)\sin(2\pi\nu_u n) \end{aligned}, \qquad (8)$$

Here, n is the number of turn, ν_u is the horizontal betatron tune and w represents x, p_x, y or p_y.

We are interested in the x-y coupling at the IP for the consideration of improving luminosity. However, we can't measure the beam oscillation at the IP in both horizontal and vertical planes directly. So two sets of turn-by-turn octopole BPM's which can differentiate the orbits of e+ and e- must be adopted for the coupling measurement. They are located 0.56m away at each side of IP respectively and inside the solenoid. Then the physical coordinates x, p_x, y, p_y at the IP can be expressed by the x and y coordinates read from the two sets of turn-by-turn BPM's through the expression of

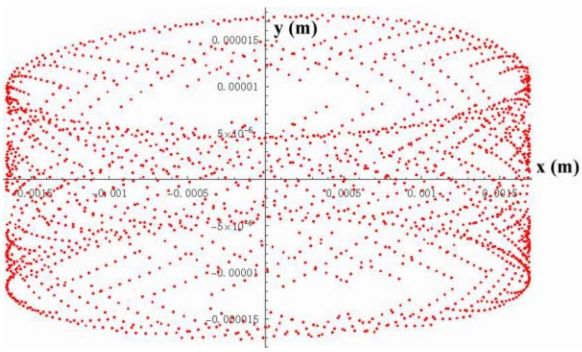
$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}_{IP} = \begin{pmatrix} m11 & m12 & m13 & m14 \\ m31 & m32 & m33 & m34 \\ n11 & n12 & n13 & n14 \\ n31 & n32 & n33 & n34 \end{pmatrix}^{-1} \begin{pmatrix} x_L \\ y_L \\ x_R \\ y_R \end{pmatrix}, \qquad (9)$$

where m_{ij} and n_{ij} are the ij-th elements of transfer matrices from the IP to the left side and right side turn-by-turn BPM's respectively. (x_L, y_L) is measured beam position at left side turn-by-turn BPM and (x_R, y_R) is at right side. The transfer matrices between the IP and BPM's can be calculated with the model lattice.

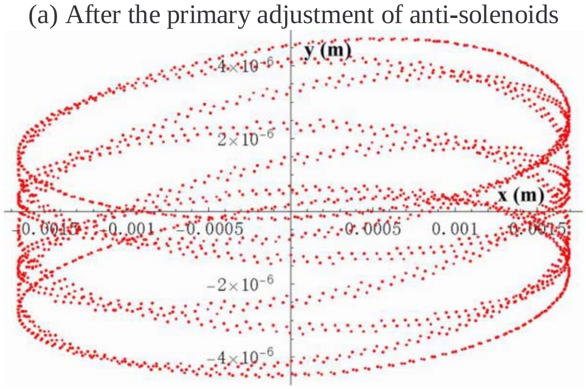
SIMULATION

The simulation of coupling measurement is based on SAD[3] code which has been chosen as the main calculating program for BEPCII. We have assumed two simulation cases for the coupling compensation. One is to control the coupling parameters only by the anti-solenoid system, the other is to control the coupling parameters by all the anti-solenoids and skew quadrupoles.

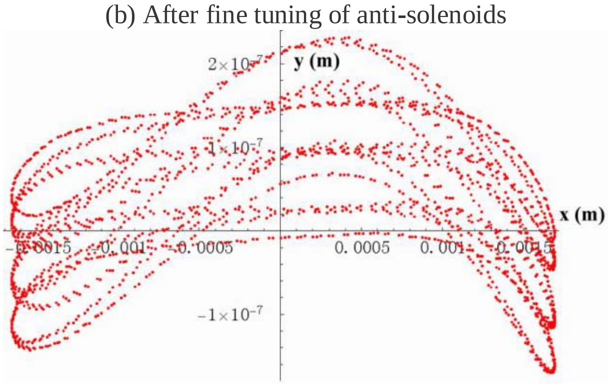
In the simulation, we build a realistic model including the horizontal shaker which is adopted in BEPCII. Moreover, we turn on the kicker that is locked at the frequency of horizontal tune to periodically kick the beam in horizontal plane. We record the transverse beam positions continuously for 1024 turns at the turn-by-turn BPM's which are adjacent to the IP. Then the physical coordinates x, p_x, y, p_y of 1024 turns at the IP can be recorded through the transformation of Eq. (10). The simulated turn-by-turn measurements at the IP are plotted in Fig. 3. (a) represents the beam transverse positions of consecutive 1024 turns only with the primary adjustment of anti-solenoids when the beam is excited in horizontal plane. (b) is the simulation result after fine tuning of anti-solenoids. (c) is the simulation result with anti-solenoids and skew quadrupole.



(a) After the primary adjustment of anti-solenoids



(b) After fine tuning of anti-solenoids



(c) With anti-solenoids and skew quadrupole

Figure 3: The simulated measurements of consecutive 1024 turns at the IP.

For the colliding mode of BEPCII, the global coupling coefficient should be controlled within 1.5% for the consideration of optimized luminosity with the beta functions at the IP of 1.0m and 1.5cm for horizontal and vertical planes, respectively. The lattice functions at the IP of three simulated data taking cases are shown in table 1. It indicates that the local coupling in the IR and the global coupling can be compensated perfectly by the combined compensation scheme and the coupling adjustment is flexible. The vertical dispersion and its slope at the IP are too small to take into account even if we do not make any particular adjustment to them. Because the skew quadrupoles are all used for the fine tuning of coupling, the required strengths of skew quadrupoles are so small that the changes of betatron tunes and beam orbit are very small too, which have been also proved by the results of compensation simulation.

Table 1: The lattice functions at the IP of three simulated data taking cases.

	After primary tuning of anti-solenoids	After fine tuning of anti-solenoids	After adding skew quadrupoles
r_1	-3.46E-4	-3.45E-4	4.687E-9
r_2	-0.003704	-0.001411	-3.23E-9
r_3	0.454186	0.092674	8.309E-7
r_4	0.001145	0.00121	6.789E-7
η_y	-1.52E-5m	2.698E-6m	9.826E-6m
η_y'	-8.44E-5	-9.00E-5	-3.10E-4
ε_x	1.54325E-7m	1.54492E-7m	1.54900E-7m
ε_y	2.9155E-10m	1.2433E-11m	5.4885E-12m
κ	0.053%	0.008%	0.004%

DISCUSSION

The coupling compensation scheme and the coupling measurement method of BEPCII have been introduced in detail. The simulation results are also shown in this paper. It indicates that the local coupling in the IR and global coupling can be compensated perfectly by the combined compensation of anti-solenoids and skew quadrupoles and the adjustment is flexible. With this compensation scheme the changes of betatron tunes and beam orbit are very small, even can be neglected during the adjustment of coupling.

It is important to have BPM's in the coupling region around the interaction region. In practice space constraints predict we can never put enough BPM's to the positions where we want. Furthermore, the systematic error of the BPM's especially for the octopole type should be well compensated to achieve the required accuracy for the measurement and analysis.

REFERENCES

[1] Y. Ohnishi, Proceedings of EPAC 2000

[2] D.A. Edwards and L.C. Teng, IEEE Trans. Nucl. Sci. **20**, 3 (1973)

[3] See http://www-acc-theory.kek.jp/SAD/sad.html