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Coupling Compensation Scheme in BEPC Ⅱ

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Abstract A new idea to compensate the coupling of BEPCⅡ will be introduced in this paper. The detector solenoid field in the 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 measure and tune the x-y coupling will be discussed in detail.

Key words coupling compensation, coupling measurement, BEPCⅡ

1 Introduction

The Beijing Electron-Positron Collider (BEPC) has been well operated not only for high energy physics, but also for synchrotron radiation application for more than 15 years since 1989. Its upgrade scheme, called BEPCⅡ, is a double-ring collider aiming at the study of τ-charm physics with a designed luminosity of $1.0\times10^{33}\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$, which is about two orders higher than BEPC. As well known, coupling will lead to an increase of vertical emittance and the tilt angle of beam profile which can reduce the luminosity obviously. The electron ring and positron ring of BEPCⅡ are almost independent, so a powerful coupling compensation system is vital to control the beam vertical size and the relative tilt angle of beam profile at the interaction point (IP). The two new rings of BEPCⅡ will be built in the existing BEPC tunnel, when keeping the function as a synchrotron radiation source. The interaction region (IR) is restricted within about ±14m long around the IP, in which twenty main magnets, thirty non-standard vacuum pumps and other equipments need to be installed. Due to the space limitation in the IR, the scheme for the dedicated coupling compensation of detector solenoid field depending on skew quadrupole families in the IR, which is adopted widely in other electron-positron colliders such as KEKB and PEP-II, can't be realized in BEPCⅡ. Therefore, we must design a special coupling compensation system to suit the constraints and characteristics of BEPCⅡ. In this paper, the design of coupling compensation and the way to measure the coupling in BEPCⅡ will be described in detail. The simulation results are given at last.

2 Normal mode analysis

We consider only the linear transverse motion in a storage ring. It has been shown by Edwards and Teng[1], Sagan and Rubin[2] that the one-turn transfer matrix in a periodical and symplectic system can be decoupled by a new transformation

$$T = Z^{-1}\cdot M\cdot Z. \tag{1}$$

Here, T and M are 4×4 one-turn transfer matrices in the physical system and normal system, respectively. In particular, M is in a block diagonal form, i.e.,

$$M = \begin{pmatrix} M_u & 0 \\ 0 & M_v \end{pmatrix}. \tag{2}$$

The normal mode coordinate $U=(u, p_u, v, p_v)$ relates to the physical coordinate $X=(x, p_x, y, p_y)$ via

$$U = Z\cdot X. \tag{3}$$

The 4×4 matrix Z is defined as

$$Z = \begin{pmatrix} \gamma I & -C^{+} \\ C & \gamma I \end{pmatrix}. \tag{4}$$

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Here I is the identity matrix and C^+ is defined as the symplectic conjugate of matrix C, $C^+ = -J\cdot C^T\cdot J$, where J is the unit symplectic matrix

$$J = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \tag{5}$$

The sub 2×2 matrices C can be defined as

$$C = \begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix}. \tag{6}$$

The relation between γ and C is $\gamma^2 + \det C = 1$. 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 Z 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

$$M_{u,v} = \begin{pmatrix} \cos(2\pi v_{u,v}) + \alpha_{u,v}\sin(2\pi v_{u,v}) & \beta_{u,v}\sin(2\pi v_{u,v}) \\ -\mu_{u,v}\sin(2\pi v_{u,v}) & \cos(2\pi v_{u,v}) - \alpha_{u,v}\sin(2\pi v_{u,v}) \end{pmatrix}, \tag{7}$$

where v_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, the particle motion in the physical coordinates[3] can be obtained from Eq.(3):

$$\begin{aligned} \gamma y &= -r_1 x - r_2 p_x \\ \gamma p_y &= -r_3 x - r_4 p_x \end{aligned}. \tag{8}$$

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 Eq. (8) into series and trigonometric function format:

$$\begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix} = -\gamma \begin{pmatrix} C_y^u & S_y^u \\ C_{p_y}^u & S_{p_y}^u \end{pmatrix} \begin{pmatrix} C_x^u & S_x^u \\ C_{p_x}^u & S_{p_x}^u \end{pmatrix}^{-1}, \tag{9}$$

where

$$\begin{aligned} C_w^u &= \sum_n w(n)\cos(2\pi v_u n) \\ S_w^u &= \sum_n w(n)\sin(2\pi v_u n). \end{aligned} \tag{10}$$

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

3 Coupling compensation

The main parameters of BEPCⅡ colliding mode are shown in Table 1.

Table 1. Main parameters of BEPCⅡ colliding mode.

beam energy E/GeV	1.89
circumference C/m	237.53
betatron tune $v_x/v_y/v_s$	6.53/7.58/0.03
harmonic number h	396
emittance $(\varepsilon_x/\varepsilon_y)$/nm·rad	153/2.3
beta function at the IP(β_x^*/β_y^*)/m	1.0/0.015
beam size at the IP(σ_x^*/σ_y^*)/μm	390/5.8
bunch length σ_l/cm	1.5
crossing angle at the IP/mrad	11×2
beam current I/A	0.91
synchrotron radiation loss U/(keV/turn)	121
damping time $(\tau_x/\tau_y/\tau_e)$/ms	25/25/12.5
luminosity L/cm^{-2}·s^{-1}	1.0×10^{33}

For the colliding mode, the detector solenoid has an effective length of ±1.8m around the IP. The maximum field strength of solenoid is 1.0T so that the particle motion between the horizontal and vertical planes will be coupled strongly. Besides the detector solenoid, the beam vertical orbit distortion inside sextupoles and machine errors including magnets fabrication and alignment errors are other main sources of coupling. Among them, the detector solenoid is the dominant. The lattice functions, the vertical emmittance and the tilt angle of beam at the IP are strongly related to the coupling. Therefore, it is impossible to meet higher luminosity without a dedicated coupling compensation system. According to the requirements of high energy physics, BEPCⅡ will be operated at the energy range from 1.0GeV to 2.1GeV, so the coupling compensation system should be powerful enough to work perfectly for particles within the relevant momentum range.

A special anti-solenoid system has been designed to realize the local compensation of x-y coupling effects in the IR. This system consists of three anti-solenoids AS1, AS2 and AS3, and a skew quadrupole SCSKQ, which are all inside the superconducting cryostat. AS1 is located between the IP and the superconducting quadrupole (SCQ), which acts as the first vertical focusing quadrupole. AS2 and the skew quadrupole SCSKQ overlap the SCQ, while AS3 is located after the SCQ. They are dedicated to the compensation of the detector fields along the beam line for both positron and electron rings, which have the same beam energy. The local compensation layout of BEPCⅡ and wiring schematic diagram are shown in Fig. 1. The superconducting magnets are being fabricated by Brookhaven National Laboratory (BNL), USA.

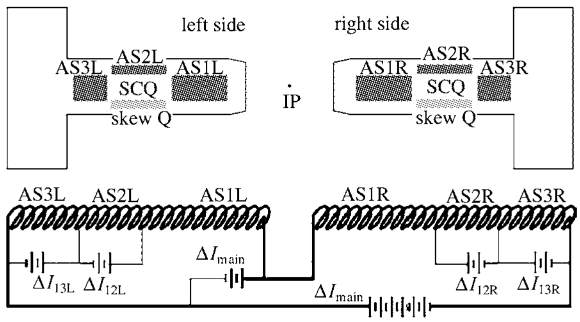

Fig. 1. The local coupling compensation layout of BEPCⅡ and wiring schematic diagram.

AS2 and AS3, which have their own independent trim circuits to allow the fine tuning of the anti-solenoid compensation scheme, are in series with AS1. Since the compensation of longitudinal field within the SCQ region is a key to control the vertical beam size at the IP, the skew quadrupole SCSKQ is used to make the fine tuning of longitudinal field over the SCQ region instead of the mechanical rotation of SCQ. With this local coupling compensation scheme, the integral field $\int B_z ds$ between the IP and the SCQ is zero. The longitudinal field over the SCQ is almost zero and the integral field $\int B_z ds$ between the SCQ and the first horizontal focusing quadrupole

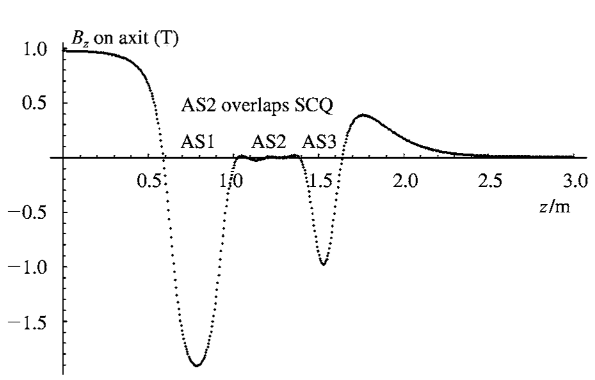

Fig. 2. The distribution of the axial combination magnetic field along the axis of the BESⅢ detector.

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

Since the anti-solenoids AS1, AS2, AS3 and the skew quadrupole SCSKQ are the common elements for both positron and electron rings, it is necessary to add some independent variables for the coupling adjustment of one ring with the coupling of the other ring unchanged. Moreover, it's impossible to completely compensate the coupling caused by the beam vertical orbit distortion inside sextupoles and machine errors only with the anti-solenoid system in the IR. Hence some skew quadrupoles located outside the IR for each independent ring are needed. Due to the space limitation, we can only arrange four normal skew quadrupoles per ring, which are distributed in the interaction region, the injection regions and the 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.

With the designed coupling compensation scheme, the global coupling parameters and the beam tilt at the IP of each ring, which are induced from the solenoid field, the beam vertical orbit distortion inside the sextupoles and the parasitic x-y coupling due to machine errors, can be controlled effectively by tuning the strengths of the skew quadrupoles and the anti-solenoids.

4 Way of coupling measurement

The global coupling parameter, which determines the beam vertical emittance, can be obtained conveniently by measuring the transverse size of synchrotron radiation light spot in the arc region, in which the synchrotron radiation monitor is installed.

The beam tilt at the IP is strongly related to the coupling parameters which have measurable effect on the luminosity. Therefore, it is very important to measure and control the x-y coupling parameters accurately for the consideration of improving luminosity. However, we can't measure the beam oscillations at the IP in both horizontal and vertical planes directly. So, two sets of turn-by-turn octopole BPM at each side of the IP, which can differentiate the orbits of positron and electron, must be adopted for the coupling measurement. While the beam is coherently excited by a shaker at the frequency of betatron tune in horizontal or vertical plane in one ring, a saturated state will be reached with the balance between sympathetic vibration and the radiation damping after a few damping times. The betatron oscillation can be measured with turn-by-turn BPM's, which are adjacent to the IP, and by using same trigger signal for the revolution. 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 BPM's through the expression of

$$\begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}_{\mathrm{IP}} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ n_{11} & n_{12} & n_{13} & n_{14} \\ n_{31} & n_{32} & n_{33} & n_{34} \end{pmatrix}^{-1} \begin{pmatrix} x_{\mathrm{L}} \\ y_{\mathrm{L}} \\ x_{\mathrm{R}} \\ y_{\mathrm{R}} \end{pmatrix}, \quad (11)$$

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. $(x_{\mathrm{L}}, y_{\mathrm{L}})$ is the measured beam position at the left side turn-by-turn BPM and $(x_{\mathrm{R}}, y_{\mathrm{R}})$ is at the right side. The transfer matrices between the IP and BPM's can be calculated with the model lattice.

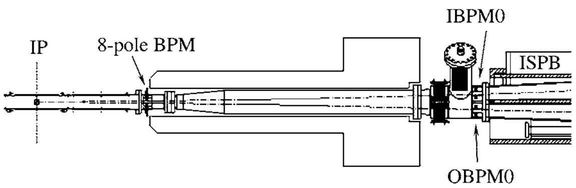

Fig. 3. The schematic view of BPMs which are distributed within the region of detector field.

The schematic view of the BPMs, which are distributed within the region of detector field is shown in Fig. 3. Since we use very flat beams, it is much more suitable to adopt a horizontal kicker instead of a vertical one for the consideration of BPM resolution while the coupling status is unchanged. For the BEPCⅡ design proposal, a horizontal shaker and two sets of turn-by-turn 8-pole BPMs, which are located ± 0.56m away from the IP, are adopted to measure the x-y coupling parameters at the IP of one ring. We record the transverse beam positions continuously for 1024 turns. Then the physical coordinates x, p_x, y, p_y of 1024 turns at the IP can be recorded through the transformation of Eq. (11). From Eq. (9) the x-y coupling parameters at the IP can be extracted from the detected betatron oscillations.

5 Simulation

The simulation of coupling measurement is based on SAD[4] 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 with the anti-solenoid system, and the other with all the anti-solenoids and skew quadrupoles.

In the simulation, we build a realistic model including a shaker, which can kick the beam in horizontal plane periodi-

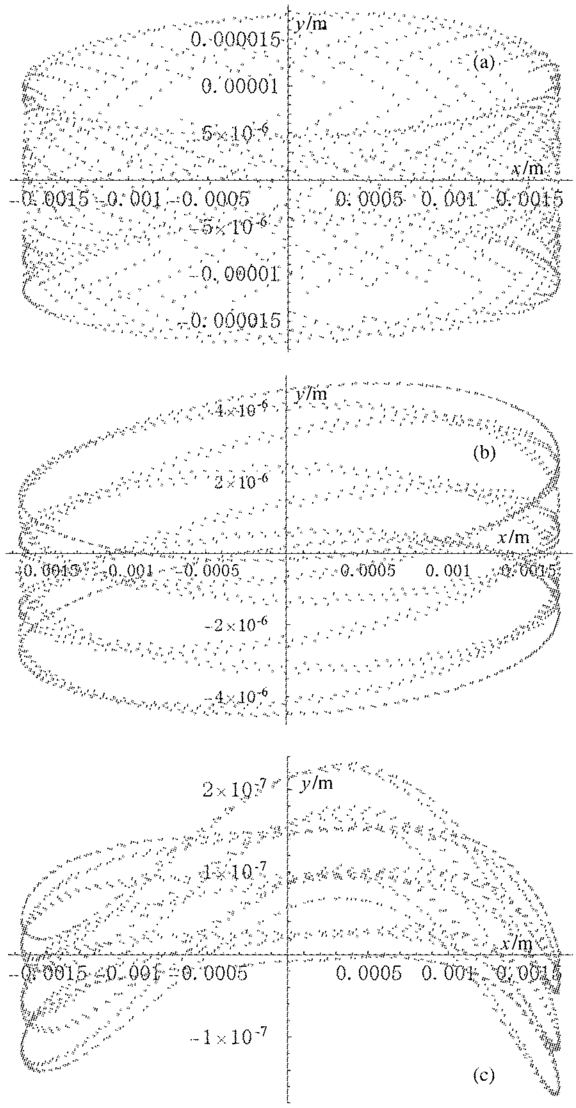

Fig. 4. The simulated measurements of consecutive 1024 turns at the IP.

(a) After the primary adjustment of anti-solenoids;

(b) After fine tuning of anti-solenoids;

(c) With fine tuning of anti-solenoids and skew quadrupoles.

cally at the frequency of horizontal tune. The shaker is turned on during the coupling adjustment and measurement. The maximum amplitude of horizontal oscillations at the IP is about 1.6mm when the saturated state is reached. We record the beam oscillations continuously at two 8-pole BPMs and transform the data to the IP. According to the FFT analysis signal of beam oscillations at the IP in the vertical plane, the strengths of the anti-solenoids AS1, AS2 and AS3 are tuned manually until the vertical oscillation meets the minimum to ensure the solenoid filed compensated locally. The measurement value of x-y coupling parameters r_1, r_2, r_3 and r_4 at the IP can be extracted from the beam oscillations. Then the four x-y coupling parameters can be tuned to zero by adjusting the strengths of four skew quadrupoles distributed outside the IR to remove the relative tilt angle of electron and positron beams at the IP.

The simulated turn-by-turn measurements at the IP with transverse beam positions for continuous 1024 turns are shown in Fig. 4. , in which (a) represents the beam transverse positions of consecutive 1024 turns only with a primary adjustment of anti-solenoids, (b) the simulation result after the fine tuning of anti-solenoids and (c) the simulation result with fine tuning of anti-solenoids and skew quadrupoles.

Table 2. The lattice functions at the IP of three simulated data taking cases.

	after primary tuning of anti-solenoids	after fine tuning of anti-solenoids	with fine tuning of anti-solenoids and skew quadrupoles
r_1	-3.5×10^{-4}	-3.5×10^{-4}	4.7×10^{-9}
r_2	-3.7×10^{-3}	-1.4×10^{-3}	-3.2×10^{-9}
r_3	4.5×10^{-1}	9.3×10^{-2}	8.3×10^{-7}
r_4	1.1×10^{-3}	1.2×10^{-3}	6.8×10^{-7}
η_y	-1.5×10^{-5}m	2.7×10^{-6}m	9.8×10^{-6}m
η'_y	-8.4×10^{-5}	-9.0×10^{-5}	-3.1×10^{-4}
ε_x	1.5×10^{-7}m	1.5×10^{-7}m	1.5×10^{-7}m
ε_y	2.9×10^{-10}m	1.2×10^{-11}m	5.5×10^{-12}m

The lattice functions at the IP of three simulated data taking cases are shown in Table 2. 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 so small and can be neglected, even if we do not make any particular adjustment in them. For the collision mode of BEPC Ⅱ, the global coupling coefficient should be controlled around 1.5% to get the optimized luminosity with the beta functions of $\beta_x^* = 1.0$m and $\beta_y^* = 1.5$cm at the IP. From the simulation results, the global coupling parameter can be adjusted easily to the design value by tuning the strengths of AS3 and four skew quadrupoles while keeping the x-y coupling parameters zero at the IP.

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 orbits are very small, which have also been proved by the results of the compensation simulation.

6 Discussions

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

During the machine operation in the future, the coupling adjustment procedures may need to be repeated for several times to satisfy the conditions of both global coupling parameter and x-y coupling at the IP. The luminosity is the only quantity that we care for. So a final online tuning of coupling should be performed to maximize the luminosity.

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

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BEPC Ⅱ的耦合补偿方案

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摘要　根据工程设计的特点和难点,BEPCⅡ储存环的耦合补偿采用了创新的设计思路. 探测器的螺线管磁场将得到对撞点两侧6块反螺线管的完全补偿,弧区内的斜四极磁铁将对全局耦合参数进行补偿与调节. BEPCⅡ耦合补偿与耦合调节的方案以及方案的可行性评估将在本文中详细介绍.

关键词　耦合补偿　耦合测量　BEPCⅡ

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