Measurement and correction of coupling in BEPCⅡ *

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Abstract: The existing linear coupling theory and representation method are introduced briefly. The so-called local and global coupling is discussed in more detail. The vertical orbit distortion excited by a horizontal corrector is represented with the coupling parameters at the corrector and the observation point. The formula is used to measure the coupling in BEPCⅡ. In order to correct the coupling, vertical correctors are used to change the vertical orbit through sextupoles by a least square method. We also introduce and review other frequently used coupling measurement/tuning methods used in our machine.

Key words: BEPCⅡ, coupling, luminosity optimization

PACS: 29.20.db **DOI:** 10.1088/1674-1137/35/12/012

1 Introduction

Quadrupole alignment errors and the non-zero closed orbit in the sextupoles will introduce coupling between horizontal and vertical directions in a storage ring. The detector solenoid in a collider can also lead to very strong coupling. The solenoid field compensation is a very important problem to be considered during the design process, since transverse betatron coupling can impact the machine performance of a collider seriously.

The coupling "contributes" to the luminosity by local coupling at the IP and global coupling. The four local coupling parameters can be represented by the Edwards-Teng-Billing parameters [1, 2]. Global coupling is often called emittance coupling ϵ_y/ϵ_x. In fact the vertical emittance comes not only from the betatron coupling but also from the vertical dispersion in an electron circular machine where the impact of radiation cannot be ignored. That is to say we need to minimize the local coupling parameters and vertical dispersion along the ring in order to reduce the vertical emittance. It is much more important to reduce the vertical dispersion in a low emittance machine such as the ILC/SuperB damping ring [3, 4].

It would be ideal if we could tune local and global coupling independently. However, the BEPCⅡ storage ring is very compact and there is no space to install magnets which could serve as the knobs. There are 4 skew quadrupoles in total in each ring, where dispersion is nearly zero. It seems that we cannot tune the local coupling, the dispersion at the IP and the vertical emission separately. That is to say, the machine tuning is much more difficult.

In the following, we first introduce the normal mode analysis of a 4D one-turn map and present the vertical closed orbit distortion excited by the horizontal corrector in a coupled machine. Then we obtain the local coupling parameters along the ring by measuring the horizontal/vertical orbit distortion excited by the horizontal dipoles. The local coupling parameters can also be obtained using a turn-by-turn beam position monitor. Since the number of Libera BPM [5] is very limited and the data are not well calibrated, so far we can not compare the results from the two methods. The familiar global coupling formula and measurement method are also introduced and discussed. The frequently used measurement and correction methods during machine tuning in daily operation are introduced in the last part of the paper.

2 Theory and simulation

2.1 Local coupling

We follow the parametrization of coupling in

Received 24 February 2011
* Supported by National Natural Science Foundation of China (10805051, 10725525)
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Refs. [1, 2, 6]. The one-turn transfer matrix of 4D phase space vector $\boldsymbol{x}=(x,x',y,y')$ is represented by $\boldsymbol{T}$, written in terms of 2×2 submatrices,

$$T=\begin{pmatrix} M & m \\ n & N \end{pmatrix}=VUV^{-1}, \quad (1)$$

where

$$U=\begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}; V=\begin{pmatrix} \gamma I & C \\ -C^{+} & \gamma I \end{pmatrix};\ \gamma^2+|C|=1, \quad (2)$$

A is a 2×2 normal mode transfer matrix, which can be represented by Courant-Snyder parameters,

$$A=\begin{pmatrix} \cos2\pi\nu_{\rm A}+\alpha_{\rm A}\sin2\pi\nu_{\rm A} & \beta_{\rm A}\sin2\pi\nu_{\rm A} \\ -\gamma_{\rm A}\sin2\pi\nu_{\rm A} & \cos2\pi\nu_{\rm a}-\alpha_{\rm A}\sin2\pi\nu_{\rm A} \end{pmatrix}. \quad (3)$$

It is similar for B. The symplectic conjugate is

$$C^{+}=\begin{pmatrix} C_{22} & -C_{12} \\ -C_{21} & C_{11} \end{pmatrix}. \quad (4)$$

In a weak coupling machine, mode A/B is similar to horizontal/vertical oscillation, respectively. $\nu_{\rm A}/\nu_{\rm B}$ is the so-called horizontal/vertical tune. The one-turn coupled transfer matrix can be rewritten in the following form

$$T=G^{-1}\bar{V}\bar{U}\bar{V}^{-1}G, \quad (5)$$

G is the Courant-Snyder transformation matrix,

$$G=\begin{pmatrix} G_{\rm A} & 0 \\ 0 & G_{\rm B} \end{pmatrix};\quad G_u=\begin{pmatrix} 1/\sqrt{\beta_u} & 0 \\ \alpha_u/\sqrt{\beta_u} & \sqrt{\beta_u} \end{pmatrix}, \quad (6)$$

$$\bar{V}=GVG^{-1}=\begin{pmatrix} \gamma I & G_{\rm A}CG_{\rm B}^{-1} \\ -G_{\rm B}C^{+}G_{\rm A}^{-1} & \gamma I \end{pmatrix}$$

$$=\begin{pmatrix} \gamma I & \bar{C} \\ -\bar{C}^{+} & \gamma I \end{pmatrix}, \quad (7)$$

$$\bar{U}=GUG^{-1}=\begin{pmatrix} R(2\pi\nu_{\rm A}) & 0 \\ 0 & R(2\pi\nu_{\rm B}) \end{pmatrix}, \quad (8)$$

where R is the rotation matrix.

We restrict ourselves to a weak coupling machine, which is true in most cases. Then $\gamma\approx1$ along the ring is a good approximation. The exception may be in the IR region, where the detector solenoid and anti-solid field is very strong. When a horizontal corrector provides a deflection θ_x, the horizontal orbit displacement is

$$\Delta x_{\rm cod}=\frac{\theta_x}{2\sin\pi\nu_x}\sqrt{\beta_{b,x}\beta_{c,x}}\cos(\Delta\phi_x-\pi\nu_x), \quad (9)$$

where $\Delta\phi_x$ is the horizontal betatron phase advance from the corrector to the observation point, β_b/β_c is the beta function at the BPM and the corrector, respectively.

The deflection in the horizontal direction would also lead to a vertical orbit displacement along the ring due to the transverse coupling. The vertical displacement comes from two parts,

1) the local coupling at BPM

$$\Delta y_{{\rm cod},1}=-\frac{\theta_x}{2\sin\pi\nu_x}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{b,22}\cos(\Delta\phi_x-\pi\nu_x) -\frac{\theta_x}{2\sin\pi\nu_x}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{b,12}\sin(\Delta\phi_x-\pi\nu_x). \quad (10)$$

We can notice that the first term on the right-hand side may come from the tilt error of the BPM, since it is in phase with that of the horizontal distortion.

2) the local coupling at the horizontal corrector

$$\Delta y_{{\rm cod},2}=+\frac{\theta_x}{2\sin\pi\nu_y}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{c,11}\cos(\Delta\phi_y-\pi\nu_y) +\frac{\theta_x}{2\sin\pi\nu_y}\sqrt{\beta_{c,x}\beta_{b,y}}\bar{C}_{c,12}\sin(\Delta\phi_y-\pi\nu_y). \quad (11)$$

We can also notice that the first term on the right-hand side may come from the tilt error of the corrector, since it is in phase with that of the vertical distortion excited by a vertical corrector at the position of the horizontal one. As a matter of fact, we do not like to use the $\bar{C}_{c,12}$ distribution as the coupling parametrization along the ring due to the finite length of magnets, since most of the horizontal correctors are implemented using the redundant coils in the main bending magnets.

According to the previous analysis, we can conclude that due to a horizontal deflection, $\dfrac{\Delta y_{\rm cod}}{\Delta x_{\rm cod}}$ at a bpm is

$$\frac{\Delta y_{\rm cod}}{\Delta x_{\rm cod}}=\bar{C}_{b,22}k_1+\bar{C}_{b,12}k_2+\bar{C}_{c,11}k_3+\bar{C}_{c,12}k_4, \quad (12)$$

where the four coefficients $k_{1,2,3,4}$ are only related to the decoupled linear optics of the machine. After the machine is well calibrated by using the LOCO method[7], it is expected that we could use the theory model to calculate the coefficients.

We performed done some simulations using SAD [8]. The rotation angle along the s-axis of quadrupoles is set randomly, then we knob the horizontal correctors and measure the transverse orbit distortion. By analyzing the orbit response information, we can get $\bar{C}_{b,12}$ at the BPMs. Tuning the vertical orbit by vertical correctors could change the coupling, where the skewed quadrupoles come from the vertical displacement through sextupoles. Fig. 1 shows the real value of $\bar{C}_{b,12}$ before/after correction. In the simulation, the emittance coupling is 6% before correction and reduces to 0.9% after correction.

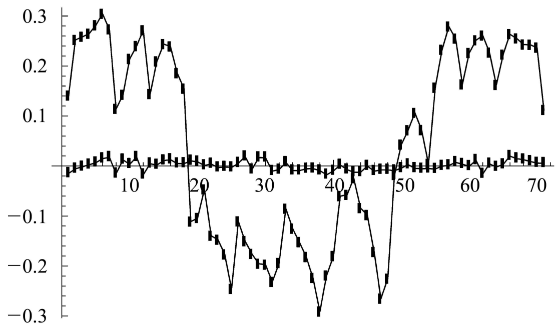

Fig. 1. Simulation study of local coupling measurement and correction. The horizontal axis is the BPM index and the vertical axis is the $\bar{C}_{b,12}$. The figure shows the real value before (dot) and after (square dot) correction.

The local coupling parameters could also be measured be using a turn-by-turn beam position monitor [9]. When only the A mode is excited, the transverse turn-by-turn beam position can be written as

$$x(n)=\epsilon_{\rm A}\gamma\sqrt{\beta_{\rm A}}\cos(2\pi n\nu_{\rm A}),$$

$$y(n)=\epsilon_{\rm A}\sqrt{\beta_{\rm B}}\sqrt{\bar{C}_{12}^2+\bar{C}_{22}^2}\cos(2\pi n\nu_{\rm A}+\Delta\phi_{\rm A}), \quad (13)$$

where n is the turn number, and

$$\cos\Delta\phi_{\rm A}\equiv\frac{-\bar{C}_{22}}{\sqrt{\bar{C}_{12}^2+\bar{C}_{22}^2}};$$
$$\sin\Delta\phi_{\rm A}\equiv\frac{\bar{C}_{12}}{\sqrt{\bar{C}_{12}^2+\bar{C}_{22}^2}}. \quad (14)$$

Inverting these expressions gives

$$\bar{C}_{12}=\gamma\sqrt{\frac{\beta_{\rm A}}{\beta_{\rm B}}}\left(\frac{y}{x}\right)_{\rm A}\sin\Delta\phi_{\rm A},$$
$$\bar{C}_{22}=-\gamma\sqrt{\frac{\beta_{\rm A}}{\beta_{\rm B}}}\left(\frac{y}{x}\right)_{\rm A}\cos\Delta\phi_{\rm A}, \quad (15)$$

where $(y/x)_{\rm A}$ is the ratio of the y amplitude to the x amplitude for the A mode.

Similarly if only the B mode is excited, we could measure the two local coupling parameters $\bar{C}_{12}$ and $\bar{C}_{11}$. Since the horizontal beam size is much larger than the vertical one in a normal electron/positron storage ring, the small amplitude oscillation in the horizontal direction is more difficult to measure. Generally speaking it is not a good idea to measure the local coupling by exciting the B mode.

2.2 Global coupling

In the smooth approximation and assuming a uniformly distributed skew quadrupolar field, analytic formulas are derived for a constant focusing lattice whose s-dependent coupling strength $j(s)$ is replaced by a uniform coupling strength given by [10]

$$C=-\frac{1}{2\pi}\oint {\rm d}s j(s)\sqrt{\beta_x(s)\beta_y(s)}{\rm e}^{-{\rm i}[\phi_x(s)-\phi_y(s)]+{\rm i}(s/R)\varDelta}, \quad (16)$$

where R is the machine radius, s is the longitudinal coordinate, β and ϕ are the Twiss parameters of the uncoupled lattice, and $\varDelta$ the fractional distance from the difference resonance. Up to the first order, $|C|$ is equivalent to the “tune difference on the coupling resonance”, $\Delta Q_{\min}$ (also known as the “closest tune approach”). Their transverse RMS emittances are coupled according to

$$\epsilon_x=\epsilon_{x0}-\frac{|C|^2}{\varDelta^2+|C|^2}\frac{\epsilon_{x0}-\epsilon_{y0}}{2}, \quad (17)$$

$$\epsilon_y=\epsilon_{y0}+\frac{|C|^2}{\varDelta^2+|C|^2}\frac{\epsilon_{x0}-\epsilon_{y0}}{2}. \quad (18)$$

It should be mentioned that the equations are given in the absence of synchrotron radiation. Recent work [11] finds that the emittance sharing and exchange driven by linear betatron coupling without radiation is much more complicated. In many cases we would like to use a more simplified equation for eliminating vertical dispersion even with radiation [12],

$$\frac{\epsilon_y}{\epsilon_x}=\frac{|C|^2}{2\varDelta^2+|C|^2}. \quad (19)$$

The minimum tune split could also be represented by the matrix formalizm[13],

$$\Delta Q_{\min}=\frac{\det|\boldsymbol{m}^{+}+\boldsymbol{n}|}{\pi(\sin\mu_{\rm A}+\sin\mu_{\rm B})}. \quad (20)$$

The most common way to adjust the coupling is to globally decouple the machine. The strengths of normal quads are adjusted to bring the normal mode tunes together. Typically the tunes cannot be made equal. The minimum tune split is used as a measure of the coupling in the machine. Skew quads are then used to minimize the tune split. Finally the normal quads are returned to their original values to bring the machine back to its normal operating point.

Bagley & Rubin have pointed out that global coupling is ill-defined [9], because the change in the $(\boldsymbol{m}^{+}+\boldsymbol{n})$ as the tunes are brought together depends on the detailed changes in the phase advances between the skew quads and the observation point. This in turn depends on which quads are used to bring the tunes together. Since most circular machines run near the coupling $Q_x = Q_y$ area, where the resonance density is low, the global coupling method helps to some extent. Detailed coupling correction needs more detailed work and we have to correct the local coupling along the ring.

3 Daily operation in BEPCⅡ

Luminosity performance strongly depends on the machine condition. The coupling correction is an important knob for optimization during daily runs, which includes the vertical emittance reduction, the local coupling and even vertical dispersion parameter tuning at the IP.

There are four skew quadrupoles in the arc, where dispersion is nearly zero. They could be used to tune the so-called global coupling parameters. At first, the power supplies are unidirectional and we seldom use the tuning method. In that case, we use the vertical orbit bump near the sextupoles as an alternative. The 3-bump vertical orbit knob near S5 (which is the most strongest sextupole in the arc) could help us tune the luminosity. It is unfortunate that we do not know for sure how the vertical emittance, local coupling or even dispersion distortion at the IP help us, we just know that they really help.

Since the autumn of 2010, the 4 skew quadrupoles in each ring have commenced operation. Most often they work as a knob of the local coupling parameter at the IP, however both the global and local couplings are changed. Since the dispersion is nearly zero at the skew quadrupoles, we ignore the vertical dispersion distortion caused by the knob.

The minimum tune split method is used to estimate the emittance coupling in BEPCⅡ, since the beam profile monitor is not well calibrated before October, 2010. One quadrupole in the injection region is used to change the transverse tune. The minimum tune separation is usually in the range of 0.01–0.02, and the coupling ϵ_y/ϵ_x is estimated about 1.0%–2.0%. The local vertical orbit 3-bump near S5 is used to change the tune separation and sometimes the minimum split can achieve 0.005. During the luminosity optimization, we do not care about the tune separation very much. In most cases we just change the bump and try to increase the luminosity. As mentioned before, the one-quadrupole knob method causes beta-beating along the ring and the minimized coupling may be enlarged when the quadrupole is resumed.

When the machine runs near the half-integer region, where the luminosity is higher, the minimum tune split method does not work since it will have to cross the synchro-betatron resonance line $2\nu_x + \nu_s = n$ when the transverse tunes move close to each other. Fischer [14] has developed a method for global coupling measurement and correction, which is based on N-turn maps fitted from turn-by-turn beam position data, where tune change is not needed. We have performed related simulations in our machine. It seems that the method does not work well. When we try to reduce the the so-called tune-split(calculated by one-turn map) at some points, it seems that the emittance coupling does not drop. We did not find a “golden” point where we could tune the coupling by its $\det|\boldsymbol{m}^+ + \boldsymbol{n}|$ value. Maybe because the machine is far from a smooth one. That may show that the minimum tune split method is not a good approximation for us.

The local coupling is obtained by analyzing the transverse orbit response to the horizontal correctors. When the detector's solenoid is off, the method is tested in the BER (the electron ring of BEPCⅡ) and the result is shown in Fig. 2.

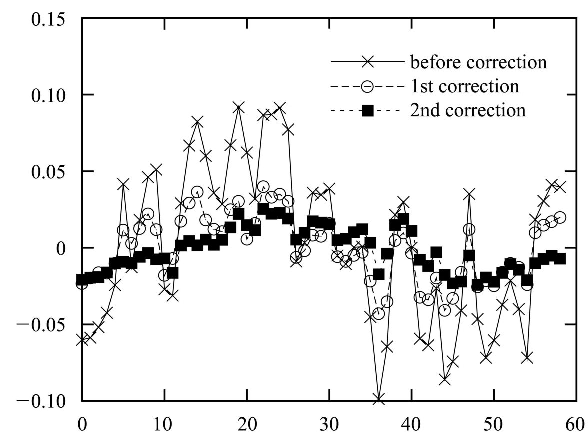

Fig. 2. Local coupling measurement and correction in the BER with the solenoid off. The horizontal axis is the BPM index and the vertical axis is the $\bar{C}_{b,12}$.

With the first correction, the vertical beam size drops from 945 to 790 (random unit), that is to say, the vertical emittance drops to 70% of the original. We also measure the Touschek lifetime by measuring the lifetime versus the bunch current and obtain that the inverse of Touschek lifetime ratio is 33:48:95 among the original, the 1st and 2nd corrections. Since the Touschek lifetime $\tau \propto \sigma_x\sigma_y\sigma_z$, we could also obtain that the vertical emittance drops by about 50% after the first correction with the lifetime data. The minimum tune split is also measured, it drops from

12 kHz to 4 kHz for the 1st and 1 kHz for the 2nd correction. It is estimated that the vertical emittance contributed by coupling drops by about 90% after the 1st correction where the Eq. (19) is used. In spite of the bad coincidence between different estimation methods, we could conclude that the coupling is significantly reduced in the ring.

When the detector solenoid and the corresponding anti-solenoid are on, the correction method has also been used successfully in our machine. Fig. 3 shows a typical example, where the rms size of $\bar{c}_{12}$ has been reduced by about 80% to 0.009.

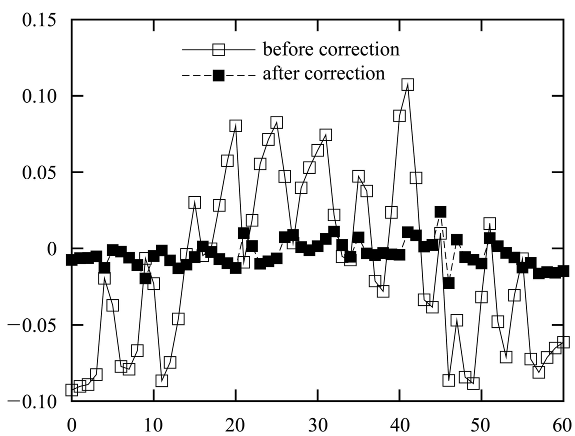

Fig. 3. Local coupling correction with the solenoid on. The horizontal axis is the BPM index and the vertical axis is the $\bar{C}_{b,12}$.

The error of local coupling measurement comes from the beta beating from the theory model and the BPM resolution. The sextupole and vertical magnet strength error would also contribute to the correction errors. Since the wiggler 4w1 is also running in the BER, the LOCO method has shown that the optic distortion is more serious in the BER than that in the BPR (the positron ring of BEPCⅡ).

The 4 transverse coupling parameters at the IP could be tuned with the 4 skew quadrupoles. An alternative method is used to change the vertical orbit in the sextupoles, where the vertical dispersion at the IP is also disturbed. That is to say, we could tune four *x-y* coupling parameters and two vertical dispersions at the IP by changing the vertical orbit in sextupoles. It is expected that the tuning would not change the orbit at the IP, injection region, RF region and north IP (where the two colliding beams are separated vertically to avoid the parasitic beam-beam effect). The preliminary experiments show that the method is not feasible since the vertical orbit distortion could not be ignored.

4 Summary & discussion

In BEPCⅡ the solenoid of the detector is well compensated by the anti-solenoid on both sides of the IP [15, 16]. It is believed that the coupling mainly comes from alignment error and the vertical orbit through the sextupoles. Coupling tuning knobs are indispensable to the luminosity optimization.

In this paper we present a formula by which we could obtain the local coupling parameters at the BPM using the orbit response information instead of the single-pass BPM. This method has been successfully used to measure and correct the coupling in our machine. We also introduce other coupling knobs for normal operation. The local coupling at the IP and the global coupling could not be tuned independently in BEPCⅡ, which would bring more trouble to the luminosity optimization. In our local coupling correction, so far we have not considered the vertical dispersion correction.

We wish to thank the members of the BEPCⅡ commissioning group for their hard work.

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