OPTICS CORRECTION IN BEPCII USING RESPONSE MATRIX *

Y.Y. Wei [#], Q. Qin, G. Xu, W.B. Liu, D.M. Zhou, Y. Chen, IHEP, CAS

P.O. Box 918, Beijing 100049, P.R. China

Abstract

The second phase commissioning of the BEPCII (Beijing Electron Positron Collider II) had been made a great progress. The optics correction using LOCO based on orbit response matrix contributed a lot to the successful commissioning. This paper discusses mainly on the procedure and results of optics correction at BEPCII. Using LOCO, we have determined the errors of quadrupole strengths, BPM gains and corrector kicks, and found the quadrupole strengths that restore the design optics well. Optics measurement after correction also shows the real optics agrees well with the design one.

INTRODUCTION

The BEPCII is constructed for both high energy physics and synchrotron radiation (SR) users. The storage ring for collision consists of a positron (BPR) and an electron ring (BER), and the outer parts of the two rings contribute to the SR ring.

To satisfy both the collision and the SR modes, the geometric and optics design of BEPCII are relatively complex. No 4-fold symmetric structure exists. The arc region consists of 6 quasi-FODO cells, and the quadrupoles and sextupoles of arc region are installed very closely. Furthermore, a number of different kinds of quadrupoles with independent power supplies are used at BEPCII, such as the superconducting quadrupole SCQs to squeeze the vertical beta function at the IP and bend the beam, the warm bore quadrupoles to connect the arc and IP, the dual aperture quadrupoles, quadrupoles inherited from BEPC, and so on. Thus, a good agreement between the real optics and the model is essential for BEPCII to achieve the optimum performance.

From the beginning of the BEPCII commissioning, we have used the orbit response matrix method base on LOCO [1] (the Linear Optics from Closed Orbits) codes to correct the optics successfully. In this paper, we present the results of BEPCII commissioning from Oct. 2007, including a brief introduction of the LOCO algorithm, the analysis and optics measurement on the three storage rings, and some problems identified by response matrix method.

THEORY

The orbit response matrix M defines the relationship between the shift at each BPM and a change in strength of each corrector:

$$\begin{pmatrix}\Delta x\\ \Delta y\end{pmatrix} = M\begin{pmatrix}\Delta\theta_x\\ \Delta\theta_y\end{pmatrix}, \tag{1}$$

where Δx, y are the orbit changes due to the changes of corrector strengths $\Delta\theta_{x,y}$. By varying the parameters in model matrix M_{model}, which is calculated by accelerator modelling code such as AT [2], the difference between model response matrix and measured matrix M_{meas} are minimized with [3]:

$$\chi^2 = \sum_{i,j}\frac{(M_{\mathrm{mod},ij} - M_{meas,ij})^2}{\sigma_i^2} \equiv \sum_{i,j} V_{ij}^2 \ . \tag{2}$$

where σ_i is the measured noise levels for the BPMs, V_{ij} is the function of the parameters varied in model lattice. With the residual error of M_{meas} and M_{model} converges to the noise level of BPM, the quadrupole gradient differences between the model and real storage ring as well as BPM gains and corrector kicks are determined. The model optics derived from LOCO after fitting can predict the real machine optics. When the gradient errors are corrected, the design optics can be restored.

ANALYSIS FOR COLLISION MODE

After the SCQs were moved to IR, we started the second phase commissioning of the BER and BPR, respectively. To make the injection relatively easier, a lattice with beta function at the IP, i.e., β_x^*/β_y^* = 2m/5cm, and the tunes of ν_x/ν_y=6.54/5.59 was chosen for both rings. Applying all the quadrupole fudge factors of last run, the beam accumulated in BER and BPR smoothly. Then we optimized the optics to the lattice of β_x^*/β_y^* = 1m/1.5cm by the lattice of β_x^*/β_y^* = 2m/3cm. When the status of beam was good enough to measure the response matrix, we attempted to do the optics correction.

Before the orbit response data was collected, beam based alignment was done to determine all BPM offsets, and orbit was corrected to the centre of quadrupoles.

There're 34 horizontal correctors, 33 vertical correctors and 67 double-view BPMs are available in both BPR and BER, respectively. This results in that (34+33)×67×2 =8978 elements can be used for fitting in model optics.

BER Optics Analysis

Response matrix was measured with sextupoles on, then we fitted the model to the measured response matrix using LOCO codes. BPM gains, corrector kicks and quadrupole strengths were varied in the model with some constraints listed as following:

- Because the change of SCQs' strength will affect the orbit, SCQs' strengths are not fitted in LOCO.

[#] weiyy@mail.ihep.ac.cn

- R3IQ1A and R3IQ1B, R4OQ1A and R4OQ1B, R3IQ02 and R3IQ03, R4OQ02 and R4OQ02 are couples of adjacent magnets which have the same polarity. If the two quadrupoles in the magnet couple are fitted independently, the strength errors derived from LOCO may fight each other. To avoid this problem only Q1Bs and Q02s in the magnet couples serviced as parameters when fitting.
- R4OQ1B and R3IQ1B are fed by the same main power supply, and different auxiliary supplies. They can only be adjusted independently within a very limit region, so their strengths vary simultaneously when fitting.

After fitting the model response matrix to the measured matrix, the rms error between them is about 0.007mm (some abnormal data removed), and the measured BPM resolution is smaller than 0.01mm. The distribution of residuals for the response matrix is normalized by the noise level of the BPMs, and the distribution has a width roughly equal to 1, which indicates the fitting in LOCO converged to the noise level of BPM.

Fig.1 shows the errors of quadrupole fudge factors. The quadrupole amplitude fudge factor *AF* describes the correction to restore the design optics:

$$K^i = AF^i \cdot K_0^i . \tag{3}$$

Here, for the i^{th} quadrupole, K is the correction strength, and K_0 is the design value. Fudge factors can be derived from the strengths found by LOCO:

$$AF^i = K_n^i / K_L^i \ . \tag{4}$$

In eq. (4), K_L is the strength determined by LOCO, and K_n the nominal strength when response matrix is measured.

From the initial result of BER fudge factors, which is shown in Fig.1 marked by “before R1OQ16 problem resolved”, we notice that the fudge factor error of R1OQ16 exceeds 15%. That means the real strength of R1OQ16 is much lower. On Dec.25, 2007, the shortcut between R1OQ16 magnet poles was confirmed. After that, we measured the response again and fitted a new set of quadrupole strengths, which is marked by “after R1OQ16 problem resolved” in Fig.1.

Furthermore, we applied the fudge factors of qudrupoles to BER. Optics measurement was performed to examine the difference between the real and the design optics.

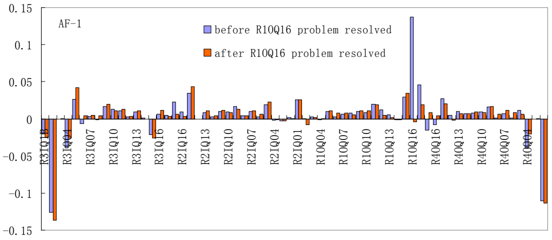

Figure 1: Errors of BER quadrupole fudge factors.

The nominal tunes of the design optics are 6.5434/5.6396, and measured tunes after correction are 6.5474/5.6377.

Beta function was measured using quadrupole modulation method. Fig.2 and Fig.3 show the comparison of the measured and design beta function. Before optics correction, beta function errors in some region even exceed 100%. After correction, the measured beta function agrees well with the design one.

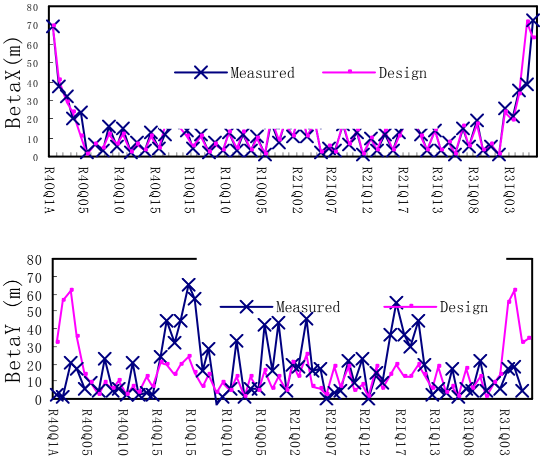

Figure 2: The comparison of the measured and design horizontal (upper) and vertical (bottom) beta function before BER optics correction.

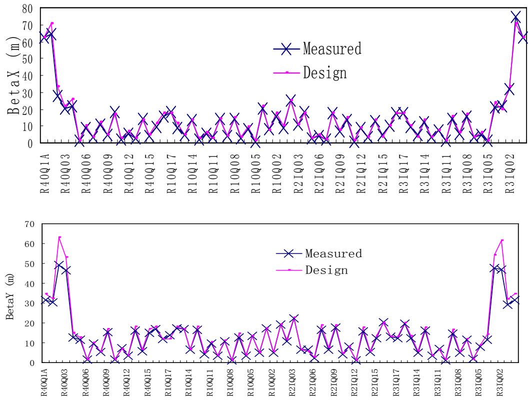

Figure 3: The comparison of the measured and design horizontal (upper) and vertical (bottom) beta function after BER optics correction.

BPR Optics Analysis

For BPR optics correction, the method and constraints fitting in LOCO are similar to BER. Only the results are presented here.

Fig.4 shows the errors of quadrupole fudge factors of BPR, marked by “SCQ:AF=1”. From Fig.1 and Fig.4 we find out the fudge factor errors of Q2s in IR are all relatively large, amounting to 10%. Because Q2s have the same polarity as SCQs, we wonder if the changes of Q2s’ strength are to compensate the SCQs’ gradient errors. Then we decreased the strength of SCQs by 0.2%, measured the response matrix and fitted. The fudge factor errors of Q2s reduced from 10% to 7%.

Additionally, in the SR mode, the SCQs are not used, and the fudge factor errors of Q2s are less than 1%. It seems to support our hypothesizer again.

Some simulations were also made. We increased the SCQs' strength by 1% in model lattice and fitted by the same way in LOCO. That is to assume the SCQs' strengths of real machine are higher than the design value by 1%. The results of BPR are displayed in Fig.4, marked by "SCQ:AF=1.01". All the Q2s' fudge factor errors of both rings appear to be less than 1%. The result of BER is similar to BPR.

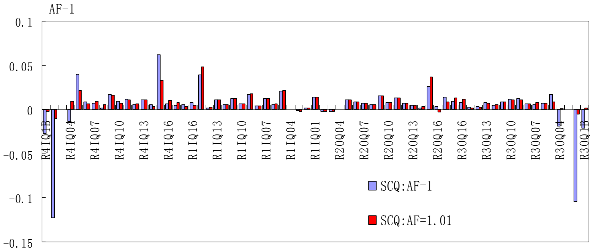

Figure 4: Quadrupole fudge factor errors of BPR with increasing SCQs' strengths by 1% in model.

All the above is not yet enough to confirm the problem on SCQs' gradients. Experiments at real machine are necessary in the future to draw the conclusion.

The optics correction of BPR succeeded to restore the design. After the fudge factors were applied, the discrepancy between the measured and theoretical beta function is within ±10% at most quadruples. For the tunes, the nominal values are 6.54/5.59, and the measured are 6.540/5.596 after correction. We also measured dispersion, as shown in Fig.5, and the deviation from design is less than 10% except for some invalid data due to bad BPMs.

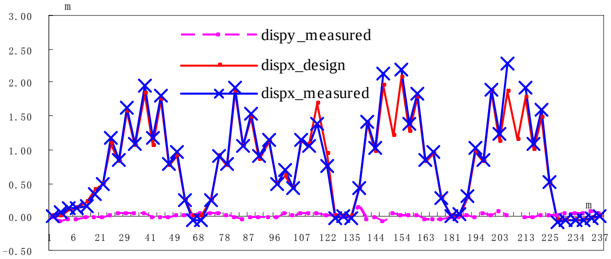

Figure 5: The comparison of the measured and design dispersion (several data is removed due to BPM problem).

Tune split method is applied to measure the transverse coupling for both BPR and BER at BEPCII. As a result, the transverse coupling of BPR is about 1.02% shown in Fig.6, and the coupling of BER is about 1.24%.

Collision tuning started based on the good agreement between the real optics and the design one. Besides the Beam-Beam Scan in longitudinal, horizontal and vertical direction, some optics including the transverse coupling is also adjusted to find out the best status of collision.

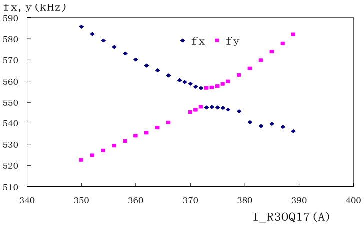

Figure 6: The measurement of BPR transverse coupling.

At BEPCII, because of the limit space, only 4 skew quads are installed in each ring, and adjusted for the IP coupling tuning locally. For the global transverse coupling, since the optics is well corrected, we can form vertical bumps across sextupoles very locally. By changing the bump height thus the vertical orbit in the sextupoles, the transverse coupling can be adjusted. In the second phase commissioning in Jan. 08, the bump height at R1IS5 and R2IS5, which have the relatively strong strengths were changed to tune the coupling of BPR and BER effectively. Parts of the results are listed in Table 1.

Table 1: The BER coupling tuning by changing the bump height at R2IS5

Bump height (mm)	Coupling (%)
0	0.477
-4	5.44
-2	2.15
-1.5	1.53
-1	1.08
-0.5	0.723

ANALYSIS FOR SR MODE

The BEPCII is a double ring collider with separated electron and positron storage rings. In the SR mode, two outer half-rings of the BSR and BER form another electron ring called BSR, which is used as a light source. The two superconducting dipole coils on the both sides of IP connect the two half-rings. The goal of SR mode is designed at 2.5GeV, and the maximum beam current is 250mA. In Mar. 08, during the second phase commissioning of BEPCII, we chose the tunes of ν_x/ν_y=7.28/5.18. The emittance at 2.5GeV is 138nm·rad.

In the SR mode, 5 wigglers are installed to produce stronger SR. Because of the vertical focusing effect caused by wigglers, the vertical tune increased by 0.08. The distortion of the vertical beta function was as much as 30%. Additionally, the effect of wigglers can change the vertical beam size and sometimes excite the structural resonances thus shorten the beam lifetime. To improve the performance of SR mode, the focusing of the wigglers must be compensated.

After orbit correction of BSR, we measured response matrix with wigglers on, and varied all the independent quadrupole strengths in LOCO to determine the changes of strength that best compensate the wiggler focusing. Actually, in the SR mode there exist 63 quadrupoles whose fields can be independently adjusted. R3OQ1A and R4OQ1A are fed by one power supply, thus their strengths must change together. The SCQs, Q1Bs and Q03s in IR are off. Additionally, a quadrupole named QSR at the north crossing point is used.

The fitting result of user mode shows the quadrupole strengths where wigglers located change intensively. We also examined the optics after correction. The tunes appeared to consist with the design value, and the beta-beating is reduced largely except for the region where wigglers located.

Understanding the Fudge Factor

Examining the errors of quadrupole fudge factor of the three rings derived from LOCO, 40% fudge factor errors exceeding 1%. Some systematic component must exist. The short distance between qudrupoles and sextupoles, and the fringe field effect may be partly responsible for the large errors.

An experiment was done at BSR based on the mode without wigglers and fudge factors applied. The nominal tunes are 7.28/5.38, the measured are 7.1685/5.2834. On one side, we increased the strengths of qudrupoles in arc by 0.6% to compensate the effect of sextupoles, the tunes measured moved to 7.1917/5.3174. On the other side, we setup the model lattice including the fringe field effect of dipoles and qudrupoles. When the modified lattice was applied to BSR, the measured tunes changed to 7.2005/5.3413. Then the two situations were all considered, the measured tunes were 7.225/5.379, which are very close to the nominal tunes on vertical direction, but still have 0.055 discrepancy left on transverse direction.

The experiment partly explained for the large fudge factors. The modified model may be adopted in fitting with LOCO in the future, and studies on other sources are still under way.

Application of Response Matrix

In the SR mode the stability of orbit is very important for the users. But in fact, the orbit drifts with time due to the effects caused by stability of power supplies, the beam, environmental temperature, and so on. To constrain the orbit drifts accurately we setup the slow orbit feedback (SOFB) system.

The SOFB system is only applied on vertical plane currently. The vertical beam size is about 100μm at the extraction point of beam line. After SOFB system applied, the orbit drift reduced from nearly 100μm to ±5~±10μm.

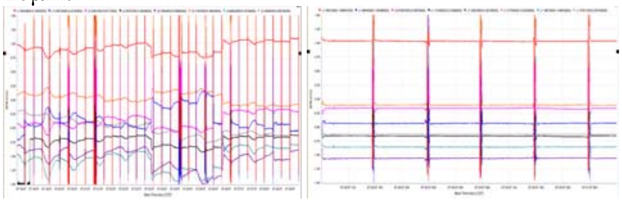

Figure 6: The orbit drifts before (left) and after (right) SOFB system is applied at the extraction points of beam lines (Jun.07, the current is 100~180mA).

During the SR runnin in June 2007, we observed several abrupt changes of orbit shown in the upper one of Fig.7. Based on the measured orbit response matrix, we found out the origin of the orbit abrupt drifts can be regard as the strength change of R2OBV07. At last, the shortcut between R2OS7 magnet poles which is located near the R2OBV07 was confirmed.

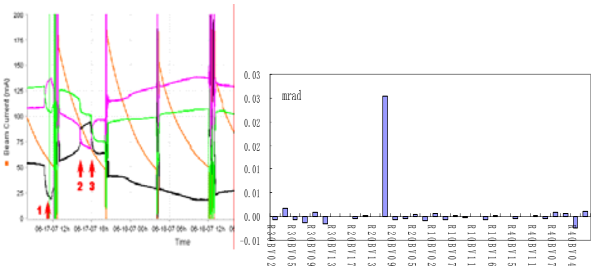

Figure 7: The abrupt changes of orbit (left) and the strength change of all vertical correctors analyzed most likely to cause the abrupt orbit changes (right).

CONCLUSION

Analysis of the orbit response matrix not only determined the quadrupole strength errors, BPM gains, corrector kicks at BEPCII, but also revealed some problems on magnets. 40% fudge factor errors of quadrupoles are more than 1%. An experiment indicates one contributed to this systemic component is the interaction of quadrupoles and their adjacent sexupoles due to their short distance. Another may be the fringe filed effect. Further studies are necessary to confirm the sources. The analysis also gave the best settings for quadrupoles to restore the design optics with sextupoles on even with all the wigglers used in SR mode. After correction, the measured beta function of BPR and BER at most quadrupoles can be restored within ±10% of design model. In SR mode, the application of response matrix method on BSR SOFB system, global orbit analysis and correction are also successful. In the future, studies on coupling correction based on response matrix, determinination the strength errors of SCQs and parasitical mode will be developed.

ACKNOWLEDGEMENTS

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