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Beam based alignment of the SSRF storage ring*

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Abstract There are 140 beam position monitors (BPMs) in the Shanghai Synchrotron Radiation Facility (SSRF) storage ring used for measuring the closed orbit. As the BPM pickup electrodes are assembled directly on the vacuum chamber, it is important to calibrate the electrical center offset of the BPM to an adjacent quadrupole magnetic center. A beam based alignment (BBA) method which varies individual quadrupole magnet strength and observes its effects on the orbit is used to measure the BPM offsets in both the horizontal and vertical planes. It is a completely automated technique with various data processing methods. There are several parameters such as the strength change of the correctors and the quadrupoles which should be chosen carefully in real measurement. After several rounds of BBA measurement and closed orbit correction, these offsets are set to an accuracy better than 10 μm. In this paper we present the method of beam based calibration of BPMs, the experimental results of the SSRF storage ring, and the error analysis.

Key words beam based alignment, SSRF, static quadrupole modulation

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1 Introduction

The Shanghai Synchrotron Radiation Facility[1] (SSRF) is a dedicated third generation synchrotron light source with nominal energy of 3.5 GeV. In the low emittance storage ring like SSRF, minimization of the closed orbit distortion is an indispensable task for the optimum performance of the machine, especially for the vertical emittance. Thus, it is necessary to have a direct measurement of the relative offset between the quadrupole's magnetic center and the BPM's electrical center. Knowing these BPM-to-quadrupole offsets allows one to make the beam pass through the magnetic center of the quadrupoles. And it brings about several benefits. First, there is no steering from the quadrupole which means that the quadrupole does not generate any orbit distortion or spurious dispersion. Second, the orbit motion caused by the quadrupole power supply jitter will be minimized. Third, the quadrupole stations in the SSRF storage ring are rigidly attached to the girders and serve as supports for the vacuum system, the BPM pickup electrodes are assembled directly on the vacuum chamber. According to the specifications of the quadrupole support and the straightness rulers on the girders, the relative offset of quadrupole magnet centers is within 50 μm and is more accurate than the ones of the BPM.

There are several popular methods used in similar machines all over the world[2]. One convenient, fast and reliable technique called static quadrupole modulation was used in our measurement. The technique has significantly increased the absolute accuracy of the SSRF storage ring BPMs since some of the measured offsets have been in excess of 1 mm.

2 Theory

Particles passing at a distance u_q from the center of a quadrupole whose strength is K receive a deflection $\Delta B = B\rho K u_q$, the effect on the orbit at

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longitudinal position s is

$$u_{\mathrm{q}i}(s)=Kl\cdot u_{\mathrm{q}}\cdot\frac{\sqrt{\beta(0)}}{2\sin\pi\nu}\sqrt{\beta(s)}\cos[\varphi(s)-\pi\nu]. \quad (1)$$

In a storage ring, there are hundreds of quadruples. If one of them is modulated by $K_{n,\mathrm{new}}=K_n+k_nK_n$, for $k_n\ll1$, suppose that the tune and beta function won't change (for the SSRF storage ring, a quadrupole strength change of $\Delta K=2\%$ introduces a tune shift about 0.005), then the transverse orbit changes as:

$$\begin{aligned}\Delta u_{\mathrm{q}i}(s) &= u_{\mathrm{q}i,\mathrm{new}}(s)-u_{\mathrm{q}i}(s)=\frac{\sqrt{\beta(s)}}{2\sin\pi\nu}\times\\ &K_nl_n\left[(1+k_n)(u_{\mathrm{q}n,\mathrm{new}}-u_{\mathrm{q}n})+k_nu_{\mathrm{q}n}\right]\times\\ &\sqrt{\beta_n}\cos[\phi_i(s)-\phi_n-\pi\nu]+\\ &\sum_{j\neq n}K_jl_j(\hat{u}_{\mathrm{q}j}-u_{\mathrm{q}j})\times\\ &\sqrt{\beta_j}\cos[\phi_i(s)-\phi_j-\pi\nu]. \end{aligned} \quad (2)$$

It can be translated into a simple function:

$$\Delta\boldsymbol{U}_{\mathrm{q}}\approx\boldsymbol{D}_n\cdot k_nu_{\mathrm{q}n}\ . \quad (3)$$

Here

$$\begin{aligned}\boldsymbol{D}_n &= (\boldsymbol{I}-\boldsymbol{C})^{-1}\boldsymbol{B}_n=(D_{in})_{N\times1},\\ \Delta\boldsymbol{U}_{\mathrm{q}} &= (\Delta u_{\mathrm{q}i})_{N\times1},\\ \boldsymbol{B}_n &= \left(\frac{\sqrt{\beta_i}\sqrt{\beta_n}}{2\sin\pi\nu}K_nl_n\cos(\varphi_i-\varphi_n-\pi\nu)\right)_{N\times1},\\ \boldsymbol{C} &= \left(\frac{\sqrt{\beta_i\beta_j}}{2\sin\pi\nu}K_jl_j\cos(\varphi_i-\varphi_j-\pi\nu)\right)_{N\times N}.\end{aligned}$$

It is clear from Eq. (3) that the orbit change from modulated quadrupole strength is a linear function of the orbit in the quadrupole. If the orbit goes though the center of the quadrupole, a subsequent change in the strength of that quadrupole will have no effect on the orbit.

According to the above analysis, by varying the beam positions in quadrupole $u_{\mathrm{q}n}$, then modulating the strength of the quadrupole and observing the change in the orbit at the BPMs, one can, in principle, determine the offset of the orbit in that quadrupole.

In order to achieve the BBA process, one must be able to individually adjust the quadrupole strength. It's also important that the BPM is located near the quadrupole in the betatron phase, because even if the beam passes through the center of the quadrupole, it may be extracted with an angle. That can produce a large error in our measurement. If then, the BPM readings can replace the beam positions in quadrupoles and offsets: $u_{\mathrm{q}n}=x_{\mathrm{BPM}}-x_0$, x_0 is the offset of the BPM quadrupole.

3 Measurement steps and procedure

As the described in the last section, there are basically two steps involved in finding the quadrupole magnet center: firstly changing the orbit in a particular quadrupole, then measuring the orbit distortion by varying the quadrupole strength. These steps are repeated several times in order to find the position of the beam orbit which creates the minimum orbit distortion. From some x_{BPM} and $\Delta u_{\mathrm{q}i}$ pairs, we can get a function $\Delta u_{\mathrm{q}i}=D_{in}(x_{\mathrm{BPM},n}-x_{0n})$ and know the quadrupole center x_{0n}. There are several methods to change the quadrupole strength[2]. A static modulation method was chosen.

From Formula (3) we know that an offset of BPMn can be got from each of the 140 BPMs in the ring. The only difference is the coefficient D_{in}. There are two data processing methods. First, defining the mean value of all BPMs fit results as the offset:

$$x_0=\sum_{n=1}^{N_{\mathrm{BPM}}}x_{0n}/N_{\mathrm{BPM}}\ . \quad (4)$$

For a more accurate measurement, a merit which considers the whole ring effect is introduced:

$$f(\bar{s})=\sum_{n=1}^{N_{\mathrm{BPM}}}(\Delta u_{\mathrm{q}n})^2=c(x_{\mathrm{BPM}}-x_0)^2\ . \quad (5)$$

The results of these two merits are shown in Fig. 1. The horizontal offset using the first merit between Q1(1,2) and BPM(1,7) is (-0.0447 ± 0.012) mm, the second one is (-0.0462 ± 0.0027) mm, and it is much better. But, as we know, if we fit higher order function we need more points. This method will cost more time.

A procedure based on the Matlab toolbox AT[3] and MML[4] is developed. Part of the main function is written by Greg Portmann[5]. It serves many functions, for example, there are four choices for how to change the orbit.

4 Experiment and result

There are 200 quadrupoles which are distributed in 20 cells of the SSRF storage ring. They are powered by digital power supply separately and the strength of the quadrupole magnets can be individually changed. Two typical cells are shown in Fig. 2. Since there are 140 BPMs, the quadrupoles very close to the BPMs are used for measurement. The BBA measurement and COD (closed orbit distortion)

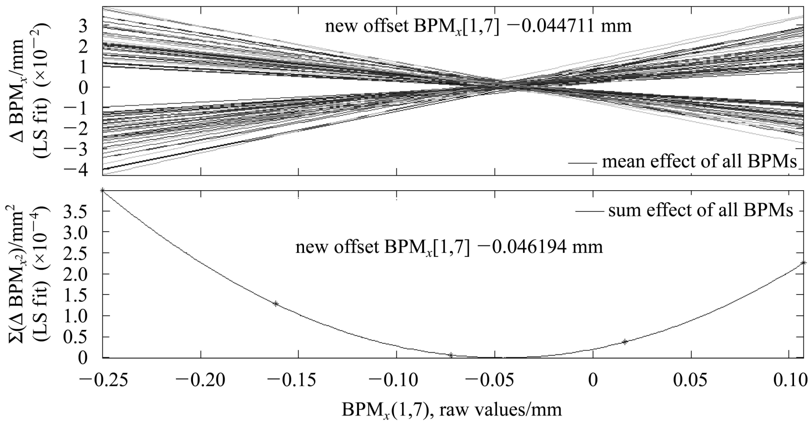

Fig. 1. Comparison of the two different merits.

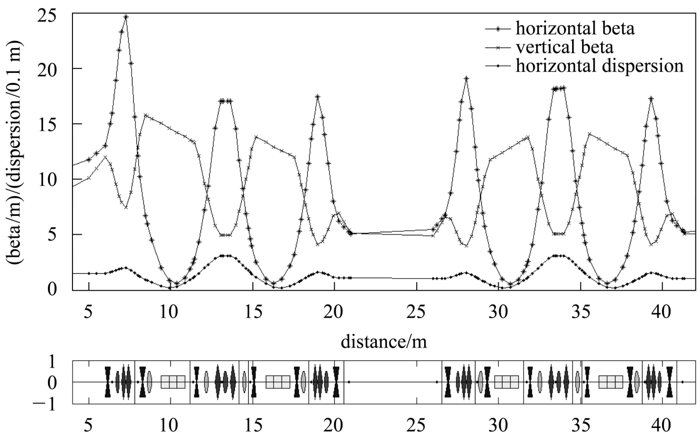

Fig. 2. Two typical cells of the SSRF storage ring.

correction are usually alternately carried out. Better results for them benefit each other. The reason is referred to the next section 3 rounds of measurement have been done. The result is gradually setting close to the real offset, and more and more accurate. The error of the vertical offset measurement is about 3 μm, and the horizontal one is about 10 μm.

The ideal size of ΔK and the corrector strength (corresponding to $\Delta u_{\mathrm{q}i}$) are carefully chosen in the measurement. If ΔK and $\Delta u_{\mathrm{q}i}$ are large, the fitting result is better due to the higher signal-to-noise ratio, but the tune shift will be large and lead to beam loss. At the same time quadrupole hysteresis will be introduced, that does not affect the fitting result accuracy very much, but it does adversely affect the machine tune since the data are computed many times. Due to the hysteresis effect, the quadrupoles need to be cycled after several magnetic centers are found. The change in quadrupole strength for this experiment was chosen based on trial-and-error. 1.5% was chosen in the first round for the glancing measurement. 2.5% of quadrupole modulation and a much smaller corrector strength were chosen in the second round for a more accurate measurement.

For each quadrupole the vertical and horizontal offsets were measured separately. Each quadrupole magnet was paired with the most effective corrector in each plane by examining the phase advance and beta functions in an attempt to maximize the change in orbit at the quadrupole.

Figure 3 shows an experimental result. Here the BPM-to-quadrupole offset determined was between Q1(1,2) and BPM(1,7). A vertical corrector VCM(5,2) in section 5 was used to change the orbit vertically, and the result is (0.02174±0.0035) mm. Fig. 4 gives the offset of all BPMs, and most of them are between ±1.2 mm. The ones which are larger than 2 mm seem to be the misalignment of vacuum chambers. It is similar to the result of other light sources in the world and it indicates that the alignment of installation is very good.

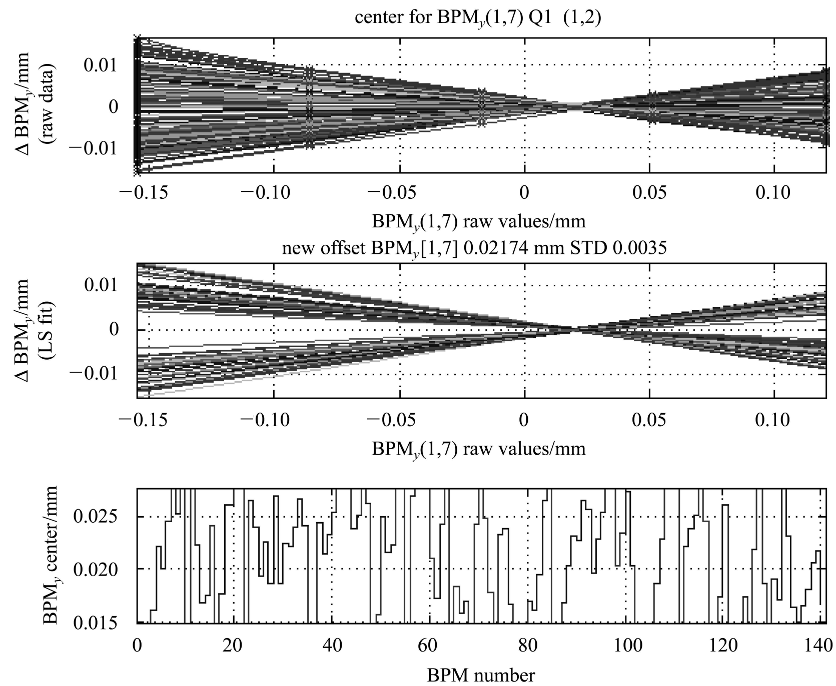

Fig. 3. Result of Q1(1,2) and BPM(1,7).

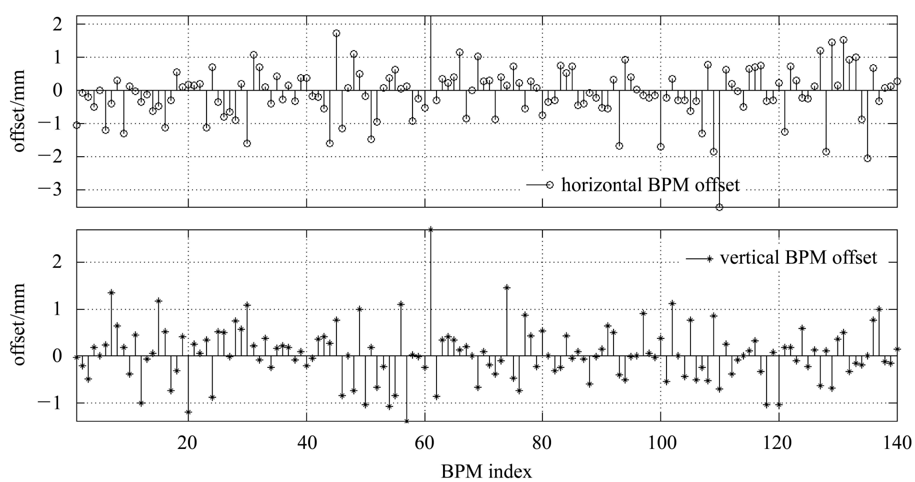

Fig. 4. Offsets of all BPMs.

5 Error analysis

There are mainly two kinds of errors in the BBA measurement: random error and systematic error. Most of these errors usually arise from the finite resolution of the BPMs. With the technique development, BPMs have submicron resolution, thus the statistical errors can be very small and, furthermore, the errors can be reduced with more data points according to the error contribution function for linear fit: $\sigma_{\rm fit}=\sqrt{\dfrac{\sigma_{\rm BPM}}{N-1}}$ (N is the data number).

In contrast, systematic errors will cause the algorithm to converge to an incorrect solution and may provide a more fundamental systemic limitation. Fortunately, the quadrupole variation beam based alignment algorithms are nulling techniques: if the beam passes through the center of the quadrupole, no deflection is produced. Therefore, any systematic errors which distort the fitted magnitude of the deflection will be decreased by iterating the procedure, provided the errors are sufficiently small that the algorithm converges.

There are several kinds of systematic errors. The first one is the nonlinear effect from the change of tune or the sextupole, the second one is energy shift from the corrector. Both of these effects can be reduced by a small as possible orbit change by the corrector, at the same time larger change of the quadrupole

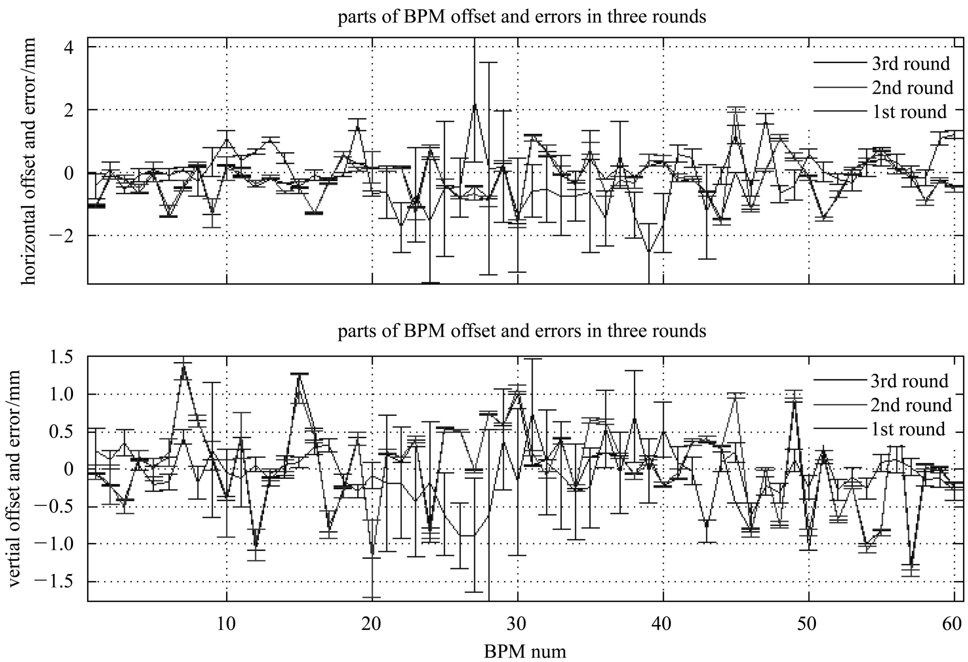

Fig. 5. Offsets and errors in 3 rounds.

strength is used in order to gain high signal-to-noise ratio. The third one is the extraction angle of beam in the quadrupole. The angle often comes from the closed orbit distortion.

That's why BBA measurement and COD correction are carried out alternately. In the first round, the COD is comparatively bad. The offset is unknown and the extraction angles are large too, we have to make large orbit change by the corrector. The accuracy is imaginably bad. But at the second round and the third round, the condition becomes better and better. Fig. 5 shows the offset errors of three rounds.

There are other error sources such as the magnetic center drifts mentioned in Ref. [6].

6 Conclusion

Higher beam current seems to give a better resolution of BPMs. After three rounds of measurement, the closed orbit deviations are corrected to less than 50 μm in both transverse planes. As we know, if the offsets are right, the closed orbit of whatever mode can be correct to a very small one. In order to prove the validity of these offsets, we have tested the closed orbit correction in several modes, and find that in each mode, we can get very good results.

This method of finding the BPM to quadrupole positional offsets has proven to be reliable and relatively fast. The accuracy of the measurement is sensitive to the BPM and power supply noise, nonlinear optics and energy shift, and the effects from these error sources can be substantially mitigated by several methods. The BPM offsets in the SSRF storage ring are typically between 0.2—1.2 mm. This technique has yielded essential data for correcting the closed orbit in the SSRF.

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