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Linear optics correction based on LOCO at SSRF storage ring*

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Abstract: Linear optics from closed orbits (LOCO) has been used during the commissioning of the Shanghai Synchrotron Radiation Facility (SSRF) storage ring. The LOCO compares a model response matrix to the real machine response matrix. Using the measured response matrix of the SSRF storage ring, the gradients in all 200 quadrupole magnets were determined, and the calibration factors of steering magnets and beam position monitors (BPMs) were obtained at the same time. After adjusting the currents of quadrupole-magnet power supplies by the maximum of 1.5%, the optics parameters were restored very close to the designed values. The horizontal and vertical differences of beta function from the design values are around 10% before correction and 1% after correction.

Key words: linear optics correction; linear optics from closed orbits; SSRF storage ring
CLC number: TL5 **Document code:** A

The Shanghai Synchrotron Radiation Facility[1] (SSRF) is a third generation synchrotron light source with nominal energy of 3.5 GeV. The storage ring consisting of 20 double bend achromatic (DBA) cells with four super-periods is designed with a workpoint of (22.22, 11.29) and low emittance of 3.9 nm • rad to provide high photon brightness. Each super-period contains three standard cells and two matching cells. There are 200 quadrupoles classed in 10 families and 140 sextupoles classed in 8 families in the storage ring. The quadrupoles are labeled Q1, Q2, Q3, Q4, Q5, and Q1L, Q2L, Q3L, Q4L, Q5L. Each of the first 5 families consists of 32 quadrupole magnets, and each of the other 5 consists of 8 quadrupole magnets[1]. Every quadrupole is excited by a separate power supply, for restoring the periods of optical functions with the presence of magnetic errors and insertion devices. During the design stage of a low emittance storage ring like SSRF, considerable efforts were made to optimize ring parameters, such as operating tunes, chromaticities, natural beam emittances and dynamic apertures[2-3]. In actual operation, however, the magnetic interference between adjacent magnets, magnetic multipole errors, and the presence of other magnets, such as insertion devices, can make the ring parameters deviate from the desired values. These unwanted errors may lead to an increase of beam emittance and a decrease of dynamic aperture. It is, therefore, very important to measure beam-optics parameters and to restore design parameters to assure successful operation of a ring. Linear optics from closed orbit (LOCO) developed by J. Safranek has been used for linear optics correction during the commissioning of the SSRF storage ring. The LOCO method compares a model response matrix to the real machine response matrix to fit quadrupole strengths[4-6]. Using this approach we are able to adjust the quadrupole strength in the real machine to match the ideal model. During the commissioning, a number of beam orbit response matrix measurements and LOCO calculations were made, and linear optics corrections were done for several operation modes[7].

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1 Theory

LOCO, widely used in many labs[8-11], is a code for analysis of the linear optics in a storage ring based on closed orbit response to steering magnets. The analysis provides information on focusing errors, beam position monitor (BPM) gain, rotation errors and local coupling. The orbit response matrix (ORM) relates the change in corrector strength to that in the orbit at BPM. A typical ORM is described as follows

$$M_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin \pi \nu} \cos(\mid \varphi_i - \varphi_j \mid - \pi \nu) + \frac{\eta_i \eta_j}{\alpha_c L_0} \tag{1}$$

where β_i, β_j, φ_i, φ_j, η_i, η_j are beta function, phase advance and dispersion at BPM and corrector, respectively; α_c, L_0, ν are momentum compaction factor, ring circumference and working point, respectively. It's clear that the ORM contains not only corrector and orbit information, but also the linear optics information. Response matrix can be calculated from given linear optics (quadrupole gradients). If the phase difference between the corrector and BPM is suitable, one can get the linear optics information from the ORM. The storage ring quadrupole gradients are determined by varying a computer model of a storage ring to minimize the χ^2 deviation between the model and measured ORMs[12].

$$\chi^2 = \sum_{i,j} \frac{[M_{\text{mod}}(i,j) - M_{\text{meas}}(i,j)]^2}{\sigma_i} = \sum_k E_k^2 \tag{2}$$

where σ_i is the measured noise level of the ith BPM; E_k is the kth element of the error vector; $M_{\text{mod}}(i,j)$ and $M_{\text{meas}}(i,j)$ are the (i,j) elements of the model and measured ORM, respectively. Differences between the ORM and the model arise from the differences in BPM gains and steering magnet calibrations as well as skew gradients, BPM coupling and steering magnet tilt. Therefore the gains, rolls, skew gradients and corrector calibrations are also fitted in the χ^2 minimization. The result is a model that best reproduces the measured response matrix. The model also accurately reproduces the beta functions, magnet gradients, BPM gains, and steering magnet calibrations of the real storage ring.

2 Error analysis

The errors in fitting parameters mainly have two parts: systematic error and random error. The error from systematic differences between the model and real rings is difficult to quantify. Typical sources of systematic error are:

(1) Magnet model limitations, such as unknown multipoles and end field effects.

(2) Errors in the longitudinal positions of BPMs and correctors.

(3) Nonlinearities in BPMs (electronic and mechanical). This part can be avoided by keeping small kick size of corrector when measuring ORMs.

(4) Nonlinearities due to sextupoles. In order to avoid this effect, in the ORM measurements and fit progress, sextupoles must be turned off. But in many machines, the dynamic aperture without sextupoles is so small that sextupoles must be turned on all the time.

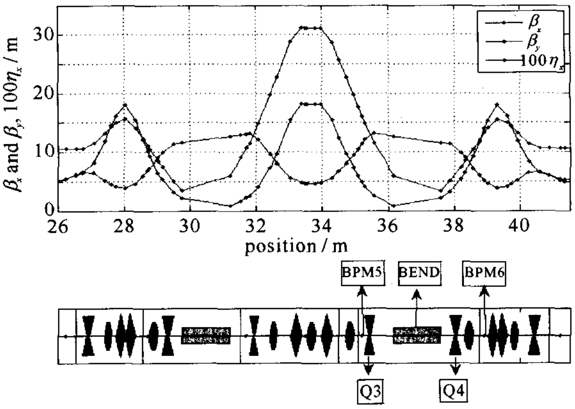


Fig. 1 Typical cell of SSRF storage ring

(5) Unsuitable phase difference between BPM and quadrupole. It is best that there was a BPM near each quadrupole. Fig. 1 shows a typical cell of SSRF storage ring. Q3, Q4 and bend magnets with undnown fringing fields would be fitted by ORM data from two BPMs far away from these elements.

The main source of random errors is BPM

noise. The fit errors should converge to

$$\chi^2/S = 1 \pm \sqrt{2/S} \tag{3}$$

where the degree of freedom $S=N-M$, N is the number of ORM data points, and M is the number of fit parameters.

In order to obtain a quantitative relation between the BPM noise levels and the fit parameters errors, some simulations were done. Fig. 2 shows the fit errors (RMS) of 20 seeds of random BPM errors about 0. 2 μm RMS. The fitted strength errors at Q3, Q4, Q5 and Q3L, Q4L, Q5L are much bigger than those at others due to the reasons referred above, however, they are still less than 0. 1% and can meet the measurement requirement of quadrupole consistency.

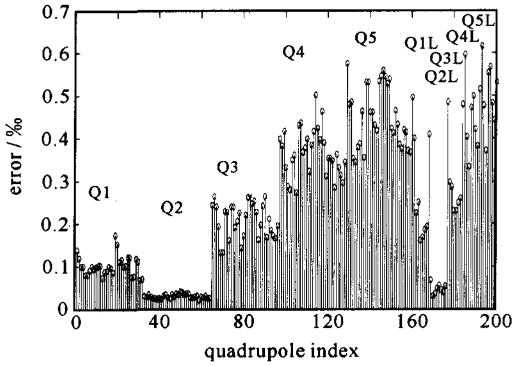


Fig. 2 Fit error with BPM measurement error about 0. 2 μm RMS

In a complicated system as an accelerator, it is impossible to eliminate systematic errors. The error bars calculated by LOCO are only lower bounds. The real errors including systematic and random ones are unknown. Yet the results are still not useless, however, they must be compared to independent measurements for confirmation and the measurements are difficult to qualify in the real machine.

3 Measurements and application

The LOCO calculations and linear optics corrections of SSRF storage ring can be divided into two stages: workpoint correction and beta function restoration.

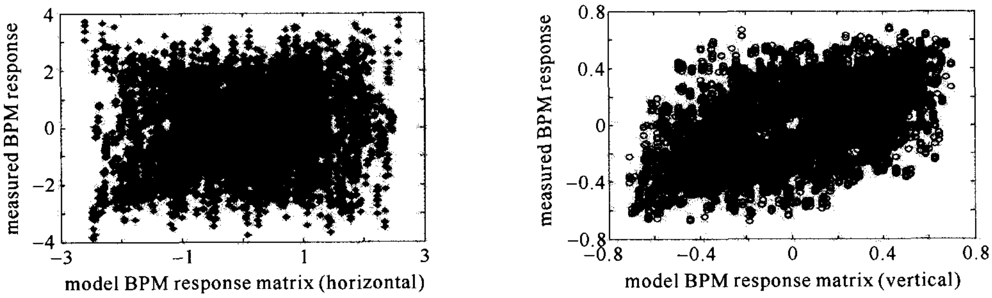
3.1 Workpoint correction

In the first days of the commissioning, the factual tunes were far away from the design values (the differences were about 1. 5 for horizontal tune and about 0. 4 for vertical tune) due to magnetic measurement errors. After several simulations of LOCO, we have found a strength scaling for all the quadrupole families, and the tune differences could be reduced to about 0. 15. The scaling comes from the magnetic measurement, which is relative. Fig. 3 shows the result of scaling. If the measured BPM ORM is the same to the model, the slope of this curve should be 1, hence the more the curve approaches 1, the more similar they are. When the integer part of tune is corrected, LOCO can take effect in the tune correction.

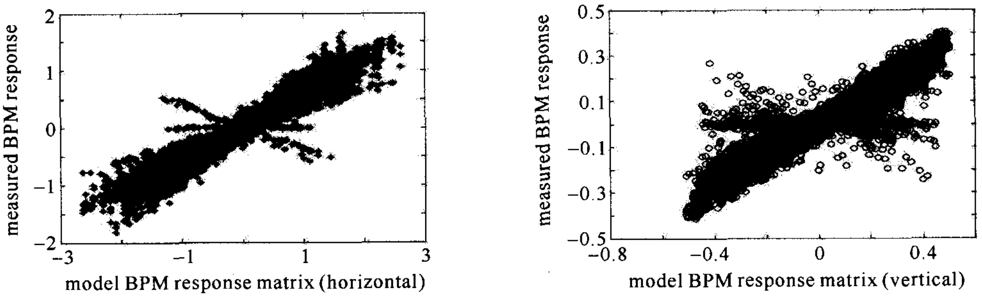
3.2 Beta function restoration

As in other third generation light sources, the lattice of the SSRF is designed with strong focusing quadrupole magnets that are necessary to generate small beam emittance. These quadrupoles produce large chromatic aberrations that need to be corrected with strong sextupole magnets. The sextupole magnets in turn generate geometric aberrations that can lead to resonance excitation. Resonance excitation would bring forth the decrease in dynamic aperture, resulting in low injection rates as well as beam lifetime shortening induced by gas and intrabeam scattering. To reduce the resonant excitation, the SSRF was designed in 4-fold symmetry. If the symmetry is broken, the resonance would increase dramatically. This makes the SSRF performance very sensitive to linear focusing errors from mispowered quadrupoles, insertion devices, and orbit errors in sextupoles. Restoration of beta function to the designed periodicity assures beam stability in a ring.

The quadrupole strengths were all included as free parameters in the LOCO fitting. The skew quadrupole winding at each sextupole was included as a free parameter, too. The resolution of each BPM was estimated by weighted fitting in the LOCO analysis. Dispersion functions were also measured. The orbit response matrix was measured with all sextupole magnets turned on because the SSRF storage ring could not operate at more than 100 mA without sextupole magnets.



(a) BPM ORM comparison before scaling



(b) BPM ORM comparison after scaling

Fig. 3 ORM comparison before and after quadrupole strength scaling

The focusing errors obtained from the LOCO fitting were applied to correct the preset strengths of the quadrupoles. The current deviations of quadrupole power supplies after several rounds of LOCO fitting and application to the real machine are shown in Fig. 4. The relative deviation was written as $\Delta k = (I_{\rm fitted}/I_{\rm coef} - 1) \times 100\%$ ($I_{\rm coef}$ and $I_{\rm fitted}$ are the quadrupole power supply's currents before and after fitting). The beta beatings (the difference between the design beta function and "real" values) before and after correction are shown in Fig. 5. The horizontal and vertical differences of beta function from the design values are around 10% before correction and 1% after correction. Compared with the beta function before correction, the beam-optics correction successfully restores the beta function to the design values and keeps good periodicity. Injection efficiency and dynamic aperture are not measured yet, however, the change in injection rate and life time proves that they are improved.

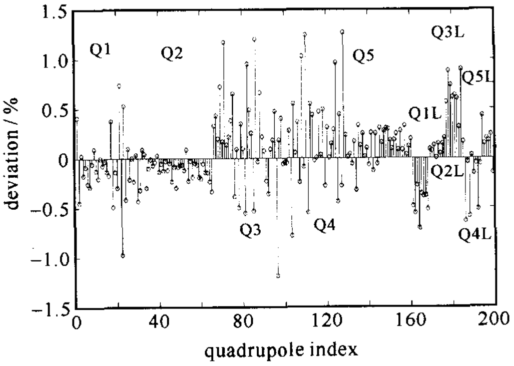
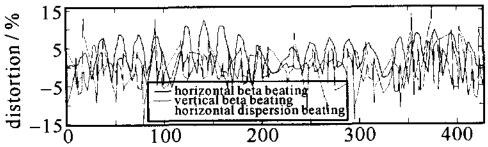
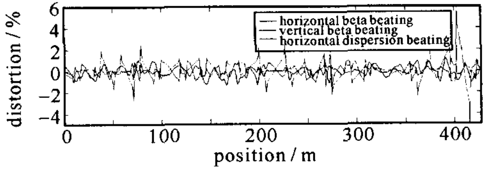


Fig. 4 Current deviations after LOCO correction



(a) beating before correction



(b) beating after correction

Fig. 5 Beta beatings before and after LOCO correction

4 Conclusion

The beam-optics distortion and subsequent correction in the SSRF storage ring were analyzed. By fitting measured response matrices to an optics model, the quadrupole field strengths were adjusted to compensate gradient errors. After optics correction, the beta functions became very close to the design values and the symmetry of the lattice was restored. As a result, the storage ring began to operate in a well-controlled mode. However, there are still much to do based on LOCO, for example, calibration of BPM gain and coupling correction, which will be carried out in next stage of study.

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基于 LOCO 的上海光源储存环线性光学参数校正

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摘　要： 为了测量和校正线性光学参数，在上海光源储存环调束过程当中使用了基于响应矩阵的线性光学参数分析（LOCO）的方法。介绍了应用 LOCO 进行计算和校正的过程，包括：数值模拟得到束流位置探测器的测量精度对拟合结果的影响，调整四极铁电源电流强度来校正工作点和 beta 函数周期性的恢复。测量结果表明，在四极铁强度调整幅度在 1.5%以内的情况下，储存环的束流光学参数成功地恢复到和设计值相当接近的状态，beta 函数和色散函数畸变小于 1%。通过束流光学参数的校正，使得在今后的工作当中可以轻松地控制储存环的工作模式。

关键词： 线性束流光学校正； 线性光学参数分析； 上海光源储存环