LINEAR OPTICS CALIBRATION AT THE HLS-II STORAGE RING USING MODEL INDEPENDENT ANALYSIS*

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Abstract

Linear optics are the main lattice parameters characterizing the linear properties of storage rings. Especially for beta function and phase advance, they are the basic lattice functions which must be accurately calibrated to ensure high quality operation of the machine. Model Independent Analysis (MIA), which adopts mathematical statistical methods to extract the effective lattice information of storage rings by directly analysing the turn-by-turn beam-position-monitor (BPM) measurements, has been applied at HLS-II to calibrate the linear optics model of the storage ring. The measurements of the turn-by-turn BPM data with all of the 32 BPMs are reported in this paper. The calibration results of the vertical beta function using MIA are presented.

INTRODUCTION

The upgrade project of Hefei light source, named HLS-II, has successfully completed in 2015 [1]. Except for all of the buildings, HLS-II is almost a new machine. A new linac has been constructed with the capability of raising beam energy up to a maximum of 960 MeV instead of the former 200 MeV linac, which has realized the full energy injection for the storage ring. The lattice structure of the storage ring has changed to 4×DBA from the former 4×TBA to provide 8 straight sections for 5 insertion devices [2, 3]. Strong focusing quadrupoles are employed to obtain lower emittance of 38 nm•rad at the nominal energy of 800 MeV in the achromatic mode. The main operation parameters of HLS-II are shown in Table 1 [4].

Table 1: Main Parameters of the HLS-II Storage Ring

Beam energy [MeV]	800
Beam current [mA]	300
Natural emittance [nm•rad]	38
Beam lifetime [hours]	8
RF Frequency [MHz]	204
Harmonic number	45
Natural energy spread (rms)	0.00047
Slow orbit drifts	< 0.1 σ
Transverse tune	4.4447/2.3597

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The performance of Hefei light source has been greatly enhanced after upgrade. In order to maintain stable operation of HLS-II, optics model of the storage ring should be calibrated and corrected accurately. The program LOCO (Linear Optics from Closed Orbits) [5] widely used for linear optics calibration around the world is adopted to calibrate the upgrade storage ring lattice and correct its optics. The measured response matrix is obtained with all of insertion devices out of work and a beam current of about 60 mA. After fitting the response matrix with LOCO, the beta functions are calibrated and corrected. The results are shown in Fig. 1.

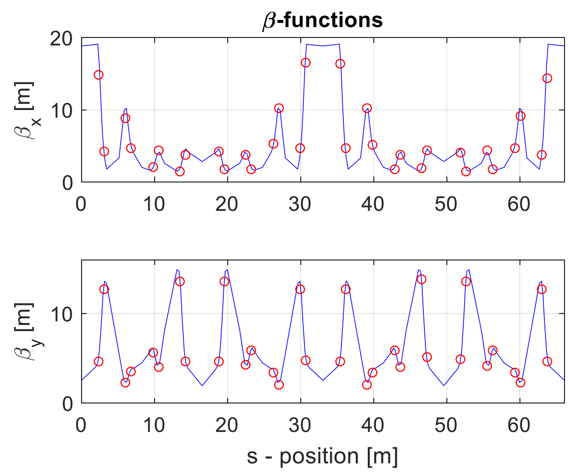

Figure 1: Transverse beta functions calibrated by LOCO in the HLS-II storage ring. The blue line shows the theoretical design value and the red circles are the calibrated values.

Because the measured of a response matrix have to change the parameters the quadrupoles, which will cause the influence of the beam operation and cannot be applied to the on-line measurement of the linear optics for the storage ring. For the sake of realizing on-line calibration of the optics model and on-line optimization of the storage ring, some new model independent methods should be studied. Thanks to the upgrade project, the whole beam position measurement (BPM) system also has been upgraded which have the ability to measure the turn-by-turn beam position. Then the model independent analysis (MIA) [6] can be adopted in HLS-II storage ring, which can calibrate the linear optics model by directly analysing the turn-by-turn BPM measurements. In this paper, the application of MIA in the HLS-II storage ring is introduced and the experiment results are presented in detail.

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MODEL INDEPENDENT ANALYSIS

Model independent analysis is a statistical signal analysis method which can be used to calibrate the linear optics by directly analysing a large number of turn-by-turn beam position measurements [7]. The turn-by-turn BPM data with enough number of BPMs can make a data matrix $B_{P\times M} = (b_p^m)$ which contains much information of the beam motion. The MIA method can analyses this data by making singular value decomposition (SVD) to the matrix.

$$B = USV^T = \sum_{\text{modes}} \sigma_i u_i v_i^T \tag{1}$$

where $S_{P\times M}$ is a rectangular matrix with non-negative singular values σ_i along the upper diagonal, which indicate the principal components of the beam motion signal. The only two biggest singular values represent the beta oscillation of the beam in the storage ring. $U_{P\times P}$ and $V_{M\times M}$ are orthonormal matrices comprising the temporal and spatial eigenvectors. The temporal eigenvectors include the temporal information that can obtain the transverse tune by Fourier analysis. The spatial eigenvectors are relevant to the transverse beta oscillation which can determine the phase advances and beta functions. The normalized spatial eigenvectors are expressed by

$$\begin{cases} v_+ = \dfrac{1}{\sqrt{\lambda_+}}\{\sqrt{\langle J\rangle \beta_m}\cos(\phi_0+\psi_m), \quad m=1,2,\cdots,M\} \\ v_- = \dfrac{1}{\sqrt{\lambda_-}}\{\sqrt{\langle J\rangle \beta_m}\sin(\phi_0+\psi_m), \quad m=1,2,\cdots,M\} \end{cases} \tag{2}$$

where $\lambda = \sigma^2$ are the eigenvalues of $B^T B$. β and ψ are beta function and phase respectively. From the Eq. (2), the phase advances and beta functions can be determined as follows.

$$\begin{cases} \beta_m = \langle J\rangle^{-1}(\lambda_+ v_{+m}^2 + \lambda_- v_{-m}^2) \\ \psi_m = \arctan(\dfrac{\sqrt{\lambda_-}v_{-m}}{\sqrt{\lambda_+}v_{+m}}) - \phi_0 \end{cases} \tag{3}$$

where $m = 1, 2, \cdots, Nbpm$. $\langle J\rangle$ is the average of the action values, which cannot be computed from turn-by-turn data. Considering that the mean action value is constant related to the lattice of the storage ring. We can calculate it by comparing one calibrated beta function and the measurement value at the same position of a BPM.

The MIA method has been verified theoretically with the lattice of the HLS-II storage ring. The turn-by-turn BPM data are calculated with theoretical model. The beta functions and phases analysed by MIA are compared with the calculated theoretical values, the results of which are shown in Fig. 2. It can be seen clearly that the analysis results fit in well with the theoretical value, which prove that this method is correct and it has potential to be used for linear optics model calibration in storage rings. Experimental analysis with this method has also been done in the HLS-II storage ring and the results will be presented in next section.

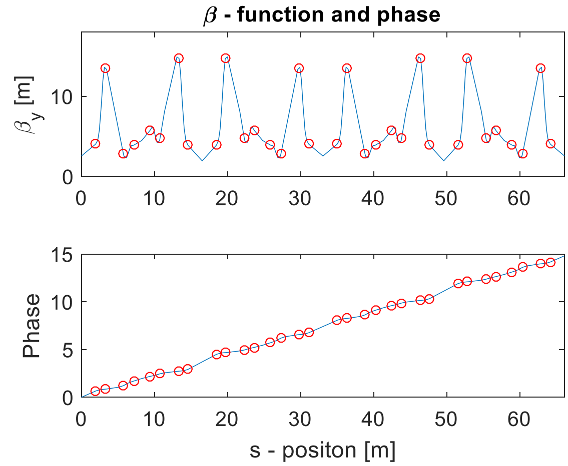

Figure 2: Comparison of the vertical beta function values. The blue line is the theoretical values and the red circles are the MIA results.

EXPERIMENT ANALYSIS WITH MIA

There are 32 BPMs in the HLS-II storage ring and each of them is capable of turn-by-turn measurement. In order to calibrate the linear optics accurately, all of other influences must be avoided, such as coupling, nonlinear effect and influence of insertion devices. Hence the turn-by-turn BPM positons should be measured in a storage ring without skew quadrupoles and insertion devices. The sextupoles can be turned off if necessary. Besides the beta oscillation of the beam should be excite to increase the signal noise ratio of the measurements. Considering the impact of nonlinear effect, the excitation amplitude must be limited to a lower level. The maximum vertical beam size of the HLS-II storage ring is about 0.15 mm and the excitation amplitude is controlled in 1 mm. Because the effect of decoherence with a kick excitation offers an extra strong signal which can affect the result precision. A harmonic oscillation is excited by a stripline kicker and the turn-by-turn measurements are taken with all of the BPM system, as shown in Fig. 3.

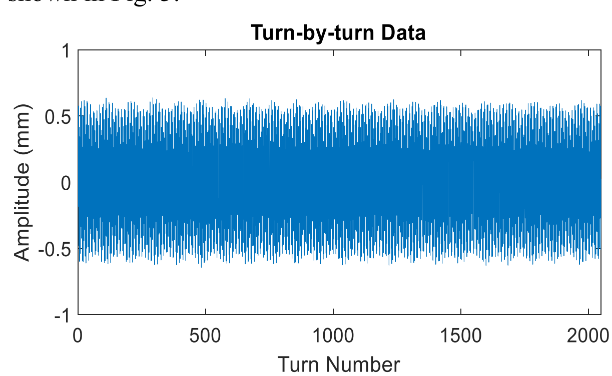

Figure 3: Turn-by-turn BPM measurements.

A matrix is constructed with 2000 turns vertical BPM measurements at each positon of 32 BPMs. The singular values, temporal eigenvectors and spatial eigenvectors are obtained after SVD analysis to the matrix. The singular values are shown in Fig. 4, which explain that the transverse beta oscillation is the principal component of the turn-by-turn signals.

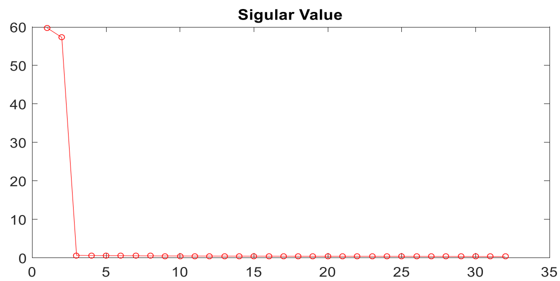

Figure 4: Singular values of the TBT matrix.

The spectrum is achieved in Fig. 5 by Fourier analysis with the temporal eigenvectors to confirm whether there are any other high order spectrums except for the vertical tunes. The analysis result tells that the nonlinear effect is very weak in the HLS-II storage ring.

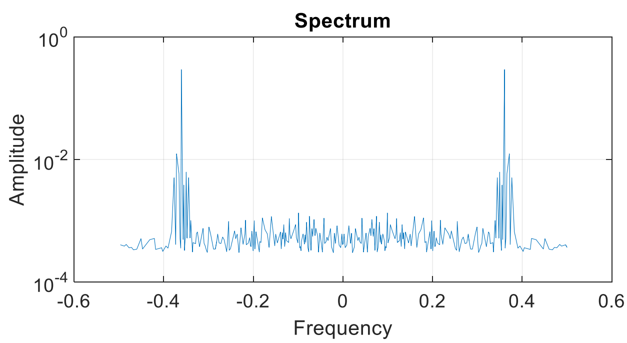

Figure 5: Fourier analysis of the temporal eigenvectors.

After analyzing with MIA method, the vertical beta function are calculated and compared with theoretical values in Fig. 6.

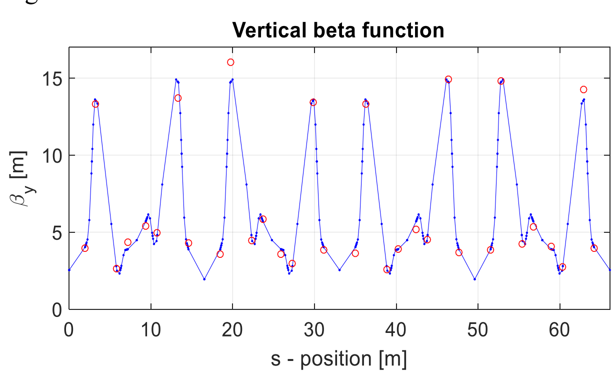

Figure 6: Comparison of the vertical beta function values. The blue line is the theoretical values and the red circles are the experiment results.

The experiment results are elementary agreement with the theoretical design. But there are still some differences which can reveal the actual performance of the machine to a certain extent. So as to increase the accuracy of the results, many repetitive experiments are done, and the differences of the results between the analysis and the theoretical design are graphical represented in Fig. 7.

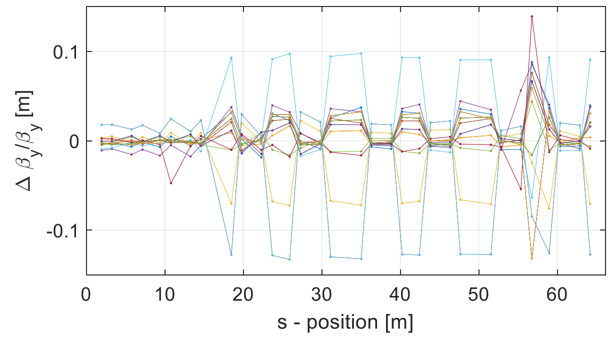

Figure 7: Beta beating results of 20 repetitive experiments.

The results show that the calibrated results with the MIA method are not very stable. Because the turn-by-turn BPM data records the comprehensive performance of the beam motion. It can be easily affected by many factors, which will reduce the accuracy of the analysis for linear optics. In spite of this, the MIA method still has great potential to on line analysis the change of storage rings.

SUMMARY

Model independent analysis can calibrates the linear optics of a storage ring by directly analysing the turn-by-turn BPM measurements rather than changing the lattice of the storage ring. In this paper, the MIA method is introduced and verified theoretically with HLS-II lattice. Especially this method is adopted for liner optics calibration for the HLS-II storage ring. A large number of turn-by-turn measurements are taken with harmonic oscillation by upgraded BPM system. The experiment results analysed by the MIA method are presented in detail.

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