15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC34

LINEAR OPTICS CORRECTION OF AN ASYMMETRIC STORAGE RING LATTICE*

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Abstract

The SSRF storage ring has been upgraded to an asymmetric lattice containing two super-bend cells, two double-mini-βy optics (DMB) cells and a superconducting wiggler (SCW) in 2019. Due to the destruction in structural symmetry, the restoration of linear optics becomes an essential issue in commissioning and routine beam dynamics maintenance. During the initial commissioning, the linear optics were well corrected with the LOCO method even though the SCW had not yet been installed. Recently, it has been found that the setups of some quadrupole power supplies tend to exceed the limits and deviate significantly from the intrinsic theoretical values, and the beta-functions and the tunes cannot be commendably recovered, leading to degradations of the storage ring performance. In this paper, the linear optics correction of the SSRF storage ring is introduced, the difficulties of the linear optics correction in asymmetric lattice are investigated, and the improved correction method and related application results are introduced.

INTRODUCTION

The accelerator upgrade in the SSRF [1] Beamline-Project mainly includes: (1) Replacing four conventional bending magnets inside two units of C03 and C13 with super-bends. (2) Creating two double-mini-βy optics (DMB) [2] in the 12-m long straight sections of D11 and D16 for dual-canted Insertion Devices (ID). (3) Inserting one SCW on a standard straight section of D12. Both upgrades (1) and (3) are designed to meet the users' demand for hard X-rays [3], and the mini gap IDs can be installed in DMB cells to obtain high-brightness X-rays while maintaining a good lifetime.

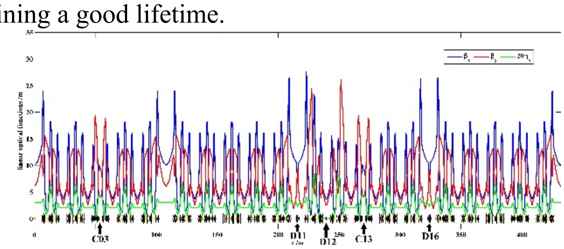

Figure 1: Linear optics and structure of the new SSRF storage ring lattice.

The lattice parameters of the newly designed SSRF storage ring [4], which exhibits high performance, are summarized in Table 1. In the new lattice, the DMB structures and the SCW were compensated in optics, while the dispersion of D12 is eliminated. The natural emittance of the new lattice was slightly elevated to 4.23 nm·rad, while optimizing the betatron tunes at 22.222 and 12.153 in both transverse planes as a precaution against potential nonlinear resonances. Figure 1 plots the linear optics and lattice layout of the new SSRF storage ring lattice, with the locations of the new elements are marked. Commissioning of the new lattice including orbit correction, linear optics correction, etc. has been completed and the upgraded machine has been put into operation. During the commissioning, the linear optics were effectively corrected using the LOCO [5] method, even in the absence of SCW installation. All lattice parameters were reached the design target. After two years of operation, it was found that the settings of some quadrupole power supplies tended to exceed the limits and deviate significantly from the intrinsic theoretical values. The imprecision in correcting the beta-functions was identified, as indicated by significant deviations of the betatron tunes from their theoretical values. This phenomenon has a detrimental impact on the performance of the storage ring. Consequently, an analysis and simulation were conducted to address this issue, resulting in a reconfiguration of the linear optics correction steps.

Table 1: Comparison of Lattice Parameters

Parameters	**New lattice**	**Old lattice**
Energy /GeV	3.5	3.5
Beam path /m	431.989	432
RF frequency /MHz	499.666	499.654
Harmonic number	720	720
Lifetime/ hrs	>10.0	>10.0
Betatron tune(H/V)	22.222/12.153	22.220/11.290
Natural emittance /nm·rad	4.23	3.89
Natural chromaticity(H/V)	-55.3/ -20.4	-55.7/-17.9
Momentum compaction factor	4.19×10^{-4}	4.27×10^{-4}
Radiation loss per turn /MeV	1.70	1.43
Relative energy spread	11.12×10^{-4}	9.83×10^{-4}

This paper presents the implementation of linear optics correction during the commissioning process for the newly

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constructed SSRF storage ring and provides a concise overview of the entire commissioning procedure. The challenges associated with correcting linear optics in an asymmetric lattice are investigated, and an improved correction method along with its relevant application results are introduced.

THE ASYMMETRIC LATTICE

The lattice with asymmetric optics is shown in Figure 1. Four 0.8m long super-bends with a working field of 2.29T can enhance the critical photon energy to 18.7 keV, and add a straight section of 2m in the middle of the cell, as well as a 2-meter long drift section under reasonable design that can be used to install short ID. The DMB structures and the SCW are compensated in optics, while the dispersion of D12 is eliminated. The natural emittance of the new lattice is moderately increased to 4.23 nm·rad. The betatron tunes are optimized to 22.222 and 12.153 in both transverse planes to avoid strong nonlinear resonances. The natural chromaticity is -55.3/ -20.4, and is corrected to a slightly positive value of 1.0/ 1.0. The diffusion map of the on-momentum dynamic aperture (DA), the on-momentum frequency map, and the momentum acceptance of the entire ring are plotted in Figure 2. The size of on-momentum DA is 30 *mm*/ 15 *mm*. In the diffusion map, only one resonance line may affect the vertical plane. RF acceptance limits momentum acceptance to roughly ±3% in straight sections, and the overall momentum acceptance is better than $\pm 2\%$.

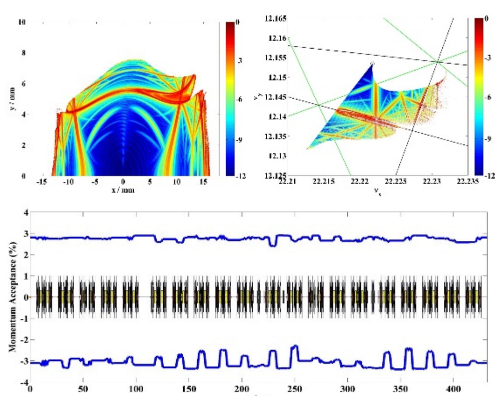

Figure 2: The diffusion map of the on-momentum dynamic aperture (DA), the on-momentum frequency map, and the momentum acceptance of the entire ring.

BEAM COMMISSONING

As an initial step in the commissioning of the new storage ring, the beam current is rapidly increased to over 100 mA by adjusting the frequency and phase of the RF system, enabling precise beam measurement and correction to be implemented. The stages of beam commissioning are organized sequentially, starting with orbit correction followed by restoration of linear optics, chromaticity correction, and optimization of nonlinear dynamics.

Orbit Correction

The beam orbit of the new SSRF storage ring is primarily distorted by the fabrication errors and the installations of the super-bends, as well as the deviations caused by the misalignments of magnets in super-bend units. As a result, the orbit correction procedure is divided into two steps, including super-bends adjustment and global orbit correction. The scanning method is used for finding the optimal current settings, and the optimization objective encompasses the beam lifetime and beam loss. For the first step, I_0 was initially fixed to the original value (710.75 *A*). Multiple scanning results suggested to set the super-bends' values of $I_1/I_2/I_3/I_4$ to 700 *A*/ 690 *A*/ 700 *A*/ 684 *A*. Local BBA for super-bend cell and global BBA are implemented after the scanning. Then, the orbit correction was performed with the new measured ORM. With this step, the RMS BPM readings are obviously reduced to 150 μm and 170 μm in both transverse planes.

Correction of Linear Optics

The optics of the new SSRF storage ring lattice is asymmetric. As of the commissioning phase, the SCW has not been installed in the machine, resulting in a discrepancy between the model corresponding to the real lattice and the designed model. The 206 quadrupoles were classified into 45 families instead of 10 families in the old lattice, achieving higher freedom for lattice tuning. The LOCO method is used to determine and restore linear optics.

The impact of missing SCW can be compensated by employing global quadrupole gradients, as the LOCO method solely fits the response matrix. The ORM, dispersion and BPM errors are measured at the beam current of 180mA for LOCO fitting. The fitting for quadrupoles is performed with the way of family-by-family, in which the whole 45 families were included.

The beta-beatings were corrected from 9.6%/ 8.9% to 1.8%/ 2.4% in RMS statistics by LOCO, the result is shown in Figure 3. The measured betatron tunes were 22.220 and 12.151 in both transverse planes, which were quite close to the theoretical values. The most important development in this step was that the beam lifetime was doubled from the low value.

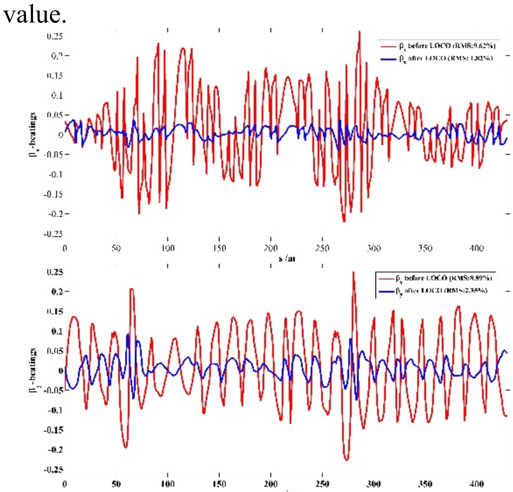

Figure 3: Beta-beatings before and after LOCO.

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Chromaticity

The sextupole families of SF, SD, SF-SB, and SD-SB are utilized for chromaticity correction. At this stage, the measured chromaticity under the previous sextupole settings is approximately 3.0/1.0. However, an excessive compensation in horizontal chromaticity is observed which could potentially lead to reduced injection efficiency and beam lifetime. To mitigate beam blow-up effects, the chromaticity is ultimately adjusted to a slightly higher value of 1.5/1.5 compared to the nominal setting.

Nonlinear Optimization

The nonlinear optimization based on the single-objective genetic algorithm is carried out after the chromaticity correction. In this process, the twelve families of harmonic sextupoles were used for optimizing the nonlinear dynamics, while the other four chromaticity-correcting sextupole families for fixing the chromaticity. The function of “fitchrom2” in AT is used for fixing the chromaticity of machine during the nonlinear optimization. The injection efficiency was defined as the unique optimal objective in the optimization process due to its high update rate and accuracy in measurement. Every optimization. Each optimization consists of 20 sets of random seeds with RMS value of 20 A, the second generation of seeds is reduced to 0.8 times the original size, and so on until the optimal solution is found. When only two successful loops were completed, it was found that the beam lifetime was significantly improved. At this moment, the lifetime was 10.49 *h* at the beam current of 210.5 *mA*, which has reached the design value.

LINEAR OPTICS CORRECTION DURING OPERATION

It is found that the current settings of some quadrupoles deviate greatly from the nominal values, and some of them even exceed the limit. In addition, the working point corrected by LOCO is much different from the theoretical value. In addition, the tunes corrected by LOCO are much different from the theoretical value.

The linear optics and betatron tunes will be distorted by quadrupole field errors, dipole rotations, and the beam deviates sextupoles’ centre. Relevant error analysis simulation is carried out, which revealed that the quadrupole field errors in the two DMB cells are most likely responsible for the anomaly in LOCO optical fitting. Figure 4 shows the simulation of LOCO fitting with quadrupole errors in DMB cells, which is very close to the fitting results of real machines. The primary factor contributing to this phenomenon may be the absence of a BPM in the DMB cells with the focusing element, resulting in challenges when fitting the response matrix in the LOCO.

In order to address the aforementioned issues, the following enhancements were implemented: 1) Manual adjustment of the quadrupoles’ current to maintain proximity to the nominal value, irrespective of tune deviations, as long as beam stability is maintained; 2) Implementation of orbit correction; 3) Removal of six quadrupole magnets from DMB cells in LOCO fitting and execution of optics correction based on LOCO; 4) Assessment and rectification of local optics within the DMB unit based on tune response to quadrupole magnet strength.

After the aforementioned operations were completed, the tunes were restored to its theoretical value. Subsequently, there was no subsequent deviation in the current direction of the quadrupole magnet over an extended period of time.

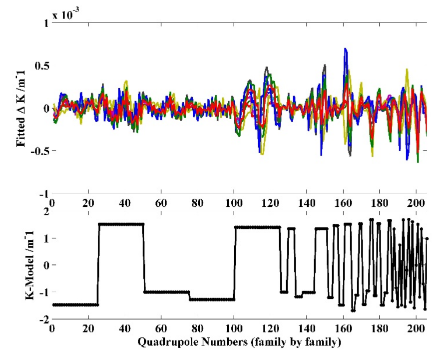

Figure 4: Simulation of LOCO fitting with quadrupole errors in DMB cells.

CONCLUSION

The lattice of the SSRF storage ring was redesigned that contains super-bend, DMB as well as SCW to maintain high brightness and to provide hard X-rays in individual beamlines. The linear optics of the new lattice are asymmetric. The DA of the new lattice is sufficient to ensure high injection efficiency and good beam lifetime. The commissioning includes the correction closed orbit, linear optics, chromaticity and nonlinear optics was completed. The optical functions were restored to the design using the LOCO technique, where the fitting process was elaborately initialized. The primary factor contributing to the phenomenon of some quadrupole power supplies tend to exceed the limits may be the absence of a BPM in the DMB cells with the focusing element. This problem was solved by manually restoring the magnet setting values and separately correcting the global optics and the local optics of the DMB cells.

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