Start-to-end commissioning simulation for the HALF storage ring

Authors: Chen, Dr. Kemin, Wang, Dr. Zhe, He, Dr. Tao, He, Duohui, Xu, Dr. Wei, Dr. Wei Xu

Date: 2025-03-10T00:00:00+00:00

Abstract

Hefei advanced light facility (HALF) is a 4th-generation diffraction-limited synchrotron light source which started construction in 2023. The storage ring has an extremely low emittance of less than 100 pm · rad with an energy of 2.2 GeV. It contains 20 superperiods of the modified hybrid 6-bend achromat with a circumference of about 480 m. A real storage ring is different from the ideal model due to various sources of errors, such as misalignment of components, imperfect magnetic fields, RF cavities, etc. As a result of strong nonlinear effects and small dynamic apertures, the errors have a serious effect on the low-emittance storage ring, which brings great difficulties to its commissioning. To figure out the practical performance of the machine with those errors, the start-to-end commission simulation is performed in this study, which also helps to verify the effectiveness of the commissioning of the HALF storage ring. In addition, the commissioning simulation process provides the basis for the development of the commissioning software for the HALF storage ring. Details and results of the commissioning simulation are reported in this paper.

Full Text

Preamble

Start-to-end commissioning simulation for the HALF storage ring

Ke-Min Chen,[1] Zhe Wang,[1] Tao He,[1] Duo-Hui He,[1] and Wei Xu[1],†
[1]National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230026, China

The Hefei Advanced Light Facility (HALF) is a fourth-generation diffraction-limited synchrotron light source that commenced construction in 2023. Its storage ring achieves an ultra-low emittance of less than 100 pm · rad at an energy of 2.2 GeV, and comprises 20 superperiods of a modified hybrid 6-bend achromat lattice with a circumference of approximately 480 meters. Real storage rings deviate from ideal models due to various error sources, including component misalignments, magnetic field imperfections, and RF cavity errors. In low-emittance storage rings, these errors severely impact performance because of strong nonlinear effects and small dynamic apectures, posing significant commissioning challenges. To evaluate the practical machine performance under these error conditions, this study conducts a start-to-end commissioning simulation, which also serves to validate the effectiveness of the HALF storage ring commissioning strategy. Furthermore, the simulation process establishes a foundation for developing the commissioning software for HALF. This paper presents detailed results and analysis of the commissioning simulation.

Keywords: HALF, Storage ring, Commissioning simulation, Beam-based alignment, LOCO.

Introduction

The HALF project aims to build a high-performance synchrotron radiation light source in the VUV to soft X-ray region. Synchrotron radiation sources offer numerous advantages, including high intensity, high brightness, transverse coherence, excellent temporal structure, and a very broad continuous spectral range [1]. Since the 1970s, dedicated synchrotron radiation light sources have evolved into one of the most powerful scientific research tools over the past decades [2]. While second-generation light sources utilize synchrotron radiation from bending magnets, third-generation light sources employ insertion devices (IDs) as the dominant radiation sources [3–5].

Fourth-generation synchrotron radiation light sources have been proposed in recent years [6]. By reducing the electron beam emittance in the storage ring, the brightness and coherence of diffraction-limited synchrotron radiation (DLSR) increase by two to three orders of magnitude compared to third-generation light sources [7, 8]. This substantial qualitative leap significantly enhances synchrotron radiation research capabilities [9]. MAX-IV, the first fourth-generation light source, employs a Multi-bend Achromat (MBA) lattice for its storage ring [10]. Since then, several other fourth-generation light sources have been constructed or upgraded from existing facilities worldwide [11–14].

The High Energy Photon Source (HEPS) is China' s first fourth-generation light source, currently undergoing commissioning [15, 16]. The Southern Advanced Photon Source (SAPS) is a medium-energy DLSR light source in the design phase [17]. Recently, an upgrade plan was proposed to transform the Shanghai Synchrotron Radiation Facility (SSRF) into a soft X-ray diffraction-limited source (SSRF-U) [18–20]. The Hefei Advanced Light Facility (HALF) is a fourth-generation light source that began construction in 2023 [21, 22]. The HALF storage ring features 20 superperiods with a modified hybrid 6-bend achromat lattice, achieving an emittance below 100 pm · rad.

In fourth-generation light sources, strong quadrupoles are employed to achieve low emittance, resulting in large negative chromaticities. To correct these chromaticities, intense sextupoles are required, leading to strong nonlinearities [23]. Due to the strong quadrupoles and sextupoles, the magnetic field feed-down effects for off-axis beams are also significant. Consequently, machine component errors can severely affect the linear optics and dynamic performance of the storage ring. Furthermore, the dynamic aperture of ultra-low emittance storage rings is much smaller than that of third-generation rings, creating additional commissioning difficulties [24].

Therefore, simulated commissioning for fourth-generation light source storage rings is essential before real machine commissioning [25, 26]. A preliminary study on simulated commissioning for the HALF storage ring was reported previously [27]. To evaluate storage ring performance and verify the effectiveness of various error corrections, this paper presents a start-to-end simulated commissioning study. The simulated correction process also establishes a foundation for future online commissioning of the HALF storage ring. This study employs a recently developed Commissioning Simulation toolkit (SC) [28] based on the commonly used Accelerator Toolbox (AT) [29].

The subsequent sections are organized as follows. Section II introduces the basic performance and layout of the HALF storage ring. Section III describes the error settings. Section IV presents the storage ring performance without any corrections. Section V outlines the correction chain of the simulated commissioning process. Section VI describes the beam optics and dynamic performance after full correction. Finally, Section VII provides summary and conclusions.

II. THE HALF STORAGE RING

A. Lattice

The HALF storage ring employs a modified hybrid 6-bend achromat lattice structure to achieve ultra-low emittance [30, 31]. The natural emittance is 85.8 pm · rad at an energy of 2.2 GeV. The ring consists of 20 identical cells, providing 20 long and 20 short straight sections. The optical functions and lattice layout are shown in Fig. 1 [Figure 1: see original paper]. Each unit cell contains 6 dipoles, 4 reverse bends, 16 quadrupoles, 8 sextupoles, and 2 octupoles. All dipole magnets are longitudinal gradient bending (LGB) magnets, which help reduce the natural emittance together with the reverse bends. The quadrupoles are independently powered to enable tuning of the optical functions. The sextupoles correct chromaticities and optimize dynamic performance. To save space, slow orbit correctors and skew quadrupole components are integrated into these sextupoles. The main parameters of the HALF storage ring are listed in Table 1 .

B. Dynamic performance

The HALF storage ring was carefully designed to optimize its dynamic performance. The on-momentum 4D and 6D dynamic apertures (DA) are shown in Fig. 2 [Figure 2: see original paper], measuring approximately 13 mm and 8 mm in the horizontal plane, respectively. Benefiting from the relatively large DA, an off-axis injection scheme can be adopted, though it still presents commissioning challenges. The local momentum aperture (LMA) is shown in Fig. 3 [Figure 3: see original paper], obtained through 6D tracking.

C. Configuration of monitors and correctors

The configuration of correctors and beam position monitors (BPMs) is shown in Fig. 4 [Figure 4: see original paper]. Each cell contains 12 horizontal and vertical orbit correctors and 12 BPMs. Among these correctors, 8 are integrated into the multifunction sextupoles, while 4 isolated correctors are located at the ends of the straight sections. Skew quadrupole coils are combined with the sextupole families SD1, SD2, and SF1 to correct coupling induced by magnet misalignment. Since the main vacuum chamber is circular with a diameter of 26 mm, a physical aperture radius of 13 mm is applied to all elements.

III. ERROR SETTINGS

Before the commissioning simulation process, various types of errors must be incorporated into the lattice to simulate the real machine. The SC toolkit is used to directly set standard errors for various components, including magnets, girders, BPMs, and RF cavities. Random errors for magnets and girders are generated based on a 2σ-truncated Gaussian distribution, where σ represents the root mean square (RMS) of the errors. Injection errors are generated based on a 3σ-truncated Gaussian distribution. The error values are taken from the HALF storage ring physics design report.

A. Misalignment and magnetic field errors

The misalignment and field errors of the main magnets are detailed in Table 2 . In a real machine, magnets are installed on girders. The magnets have misalignment errors, and the girders also have misalignment errors. Therefore, the overall magnet misalignment is the sum of both individual magnet errors and girder errors. The fields of bends and quadrupoles are set with an RMS fractional error of 5$\times10^{-4}. The RMS field errors of other multipoles are set to 1\times10^{-3}$.

B. BPMs and correctors

The BPM turn-by-turn (TBT) data resolution is set to 1 µm, and the resolution for closed orbit slow acquisition (SA) data is set to 0.1 µm. A 3% calibration error is assumed for the sum signal. The maximum strength of orbit corrector magnets (CMs) is 1 mrad in both horizontal and vertical planes. To correct ring coupling, skew quadrupoles with a maximum strength of 0.27 m^{-2} are employed. The BPM and corrector parameters are shown in Table 3 .

C. RF errors

RF system errors include frequency, voltage, and phase errors, which primarily arise from calibration, system drift, closed orbit errors, and beam energy errors in the storage ring. RF cavity error information can be obtained through beam transmission. The initial phase error of the RF cavity is typically large. The RF system errors are presented in Table 4 .

D. Injection errors

As a fourth-generation light source, the HALF storage ring has a relatively large dynamic aperture, which significantly improves ring acceptance and enables the use of an off-axis injection scheme. The HALF injection system adopts the pulsed nonlinear kicker (NLK) method [32, 33], which features a simple structure and minimal disturbance to the stored beam. Using the pulsed NLK, the injected bunch is directly kicked into the storage ring' s acceptance in phase space. The injected beam then damps onto the stored beam' s closed orbit after several damping times. The stored beam passing through the central field-free region experiences minimal impact from the NLK, making the injection transparent to light source users.

A full-energy linac at 2.2 GeV serves as the storage ring injector. The injected beam from the linac has an emittance of 500 pm • rad. The NLK and a septum are located in one straight section, forming the complete injection system. The injected beam parameters at the injection point are shown in Table 5 , and the errors are described in Table 6 .

IV. PERFORMANCE BEFORE CORRECTION

To understand the difference between the ideal lattice and the actual lattice with errors, the HALF storage ring performance was studied without any corrections. In fourth-generation light sources, the closed orbit (CO) may be absent without correction. The CO existence is investigated by scaling the global error factor, as shown in Fig. 5 [Figure 5: see original paper]. The global error factor directly multiplies all individual RMS errors listed in the error tables in Section III. The closed orbit is calculated using the 'findorbit4()' function with RF off and 'findorbit6()' with RF and radiation on. To simulate real-world conditions, closed orbits are obtained using 'findorbit6()' in the following study. For each global factor, 600 sets of random seeds are used to calculate the existence probability. The results show that the CO exists when the scaling factor is less than 20%. As the factor increases to 100%, the CO existence probability decreases to less than 20%. When the factor reaches 170%, all closed orbits are absent. The CO deviation as a function of the global error factor is shown in Fig. 6 [Figure 6: see original paper]. The deviation increases with the global error factor until the closed orbit is lost. When the factor reaches a certain level, the orbit deviation reaches its maximum before beam loss. These results indicate that the CO is highly likely absent at the beginning of real machine commissioning. Therefore, start-to-end simulated commissioning is essential for fourth-generation light source storage rings to validate real machine commissioning procedures.

V. SIMULATED COMMISSIONING FOR THE HALF STORAGE RING

This section presents the correction chain for the HALF storage ring simulated commissioning, which includes: A) Initial transmission correction (first-turn and second-turn trajectory correction), B) Trajectory beam-based alignment, C) Injection correction, D) Sextupole ramping, E) RF correction, F) Beam-based alignment, and G) Optics correction. To avoid influence from sextupoles and the RF system on beam dynamics, they are turned off at the commissioning start. For the HALF storage ring, the radiation loss per turn for a single particle is 181.4 keV, and the linear energy acceptance is 8.1%. Therefore, the maximum beam transmission is 987 turns with RF off. In the commissioning simulation, we assume all hardware is properly installed with no low-level errors such as magnet polarity reversal or BPM malfunctions.

A. Initial transmission

At the beginning of ring commissioning, the beam often fails to form a closed orbit and may not complete a full turn. Achieving initial beam transmission is crucial in fourth-generation light source storage rings. To obtain the first-turn beam, trajectory correction is performed using the trajectory response matrix of the ideal lattice. Before correction, particles must travel some distance in the storage ring so that some BPMs can acquire turn-by-turn beam position signals. If no BPMs have signals, one can try scanning the injected beam position. Alternatively, wiggling the strengths of orbit correctors upstream of the first BPM is another method.

The trajectory correction system consists of BPMs with beam signals and correctors located before the last BPM with a signal, as shown in Fig. 7 [Figure 7: see original paper]. Using this system, the trajectory can be corrected to approach the BPM centers. This correction aims to enable more BPMs to acquire position signals. If ineffective, one can attempt to change corrector strengths in the correction system until the beam passes through more BPMs. Another solution is to change the injected beam position and restart correction from the beginning [34]. The first-turn beam is obtained when all BPMs have beam signals. To extend beam travel, the first-turn trajectory correction can be repeated multiple times. After first-turn trajectory correction, particles are expected to survive for tens of turns. To further improve transmission, the second-turn trajectory is corrected to match the first turn. This is typically done by adjusting several correctors upstream of the injection point and observing several BPMs downstream, as shown in Fig. 8 [Figure 8: see original paper]. After second-turn trajectory correction, more turns are expected from the injected particles. The cumulative distribution functions (CDFs) of beam loss under first-turn and second-turn trajectory corrections are shown in Fig. 9 [Figure 9: see original paper].

B. Trajectory beam-based alignment

Due to magnetic field feed-down effects, the electron beam receives a kick when traveling away from quadrupole centers. This additional kick significantly impacts beam transmission, particularly in low-emittance storage rings with strong quadrupoles. To avoid this effect, the beam should pass through the centers of all quadrupoles. The beam-based alignment (BBA) technique determines the center of a quadrupole using a nearby BPM and orbit correctors.

The beam position $X(s_0)$ (trajectory or orbit) at quadrupole position s_0 can be described as $X(s_0) = x_0\hat{x} + y_0\hat{y}$, where x_0 and y_0 are particle offsets relative to the quadrupole magnet center in the horizontal and vertical planes, respectively.

Due to the feed-down effect, the quadrupole generates a dipole field: $Bx = B_{0\ 0}Ky_0$, $By = B_{0\ 0}Kx_0$, where $B_{0\ 0}$ is the magnetic rigidity and K is the normalized quadrupole strength.

By changing the quadrupole strength by ΔK, the dipole field variation is given by $\Delta Bx = B_{0\ 0}\Delta Ky_0$, $\Delta By = B_{0\ 0}\Delta Kx_0$.

For the closed orbit scenario, this variation results in an orbit change at location s [35]:

$\Delta X(s) = \Delta K\ T(s,s_0)\ X(s_0)$,

where

$T(s,s_0) = (\sqrt{(\beta(s)\beta(s_0))}\ /\ (2\sin(\pi\ )))\times\cos(|\ (s)\text{-}\ (s_0)|\text{-}\pi\ )$,

with $\beta(s_0)$ and $\beta(s)$ being the beta functions at the quadrupole and observation points, (s_0) and (s) the betatron phases, and the betatron tune.

The function $T(s,s_0)$ relates to the Courant-Snyder (C-S) parameters and can be considered constant for small quadrupole strength changes ΔK. Consequently, the orbit change $\Delta X(s)$ is proportional to the orbit offset $X(s_0)$. If the beam passes through the quadrupole center, the orbit change should theoretically be zero. Using this principle, the quadrupole center can be determined by measuring orbit changes while varying the beam position in the quadrupole through strength changes ΔK [36]. If the beam orbit is least affected by changing the target quadrupole strength, the nearest BPM reading is considered the quadrupole center.

The BBA process can also be applied to trajectories. The difference is that for trajectory BBA, beam position changes are generated by adjusting the initial conditions of the injected beam. After trajectory BBA, the beam loss CDF is shown in Fig. 10 [Figure 10: see original paper]. To improve visibility of surviving turn changes, the x-axis of subsequent figures is limited to [10^2, 10^3]. The results show that trajectory BBA provides no significant improvement in beam transmission. The reasons are as follows: First, the beam' s stable region is very narrow at this stage, and scanning the injected beam may disrupt effective beam accumulation. Second, the low number of transmitted turns is insufficient to generate Slow Acquisition (SA) data, so TBT data are used for trajectory BBA. However, TBT data accuracy is affected by inadequate signal-to-noise ratio due to low beam charge. Therefore, trajectory BBA does not play a significant role in the commissioning simulation, though it remains worth attempting in real machine commissioning.

C. Injection correction

To correct static injection errors, injection correction is needed to optimize the injection position. This correction aims to make the first-turn trajectory close to the second-turn trajectory. Beam positions upstream and downstream of the injection point are used. In Fig. 11 [Figure 11: see original paper], the first-turn BPM reading upstream is (xu, yu), and the second-turn BPM reading downstream is (xd, yd), where xu,d and yu,d are BPM readings in horizontal and vertical planes, respectively. The distances between the BPMs and injection position are lu and ld. The injection point can then be moved to:

x_{inj} = (ld · xu - xd · lu)/(lu + ld) + xd, y_{inj} = (ld · yu - yd · lu)/(lu + ld) + yd.

The injection angle is given by:

_x,inj = (xd - xu)/(lu + ld), _y,inj = (yd - yu)/(lu + ld).

The beam loss CDF after injection correction is shown in Fig. 12 [Figure 12: see original paper]. The results indicate that injection correction somewhat contributes to injected beam survival but does not play a major role. However, this method remains worth trying in real machine commissioning by scanning more injection points.

D. Sextupole ramping

Due to large nonlinear effects induced by sextupoles, they are turned off at commissioning start. For storage rings, chromatic sextupoles are needed to correct chromaticities to positive values to avoid head-tail instability. Harmonic sextupoles are also commonly employed to optimize storage ring dynamic performance. For sextupole ramping, all sextupole strengths are increased in five steps. After each step, the trajectory is corrected to the reference trajectory obtained from trajectory BBA. If necessary, transverse tunes can be adjusted by scanning two quadrupole families to improve beam transmission. For an operational storage ring, a tune knob system can correct tunes while maintaining periodicity and global optics functions [37]. Here, at the commissioning stage, a simple method using only two quadrupole families is adopted for transverse tune scanning. Up to this point, synchrotron radiation from all magnets is active while the RF remains off. After sextupole ramping, approximately 600 turns are achieved, as shown in Fig. 13 [Figure 13: see original paper]. This is reasonable compared to the ideal case of 987 turns mentioned previously. Next, the RF is turned on to form the closed orbit.

E. RF correction

BPM turn-by-turn (TBT) data can be used to correct RF system phase and frequency errors. Due to horizontal dispersion, the horizontal beam position change Δx induced by energy variation ΔE is described as [38]:

$\Delta x = \ x(\Delta E/E)$, (12)

where x is the horizontal dispersion and E is the beam energy. The beam energy variation with turn number n can be expressed as [39]:

$\Delta E\_n = eV \sin(\Delta\omega T_0 n + \phi_0 + \Delta\phi) - U_0$, (13)

where V is the RF voltage, ϕ_0 the synchronous phase, T_0 the synchronous period, U_0 the radiation energy loss, and $\Delta\omega$ and $\Delta\phi$ the frequency and phase differences from ideal values.

By integrating Eq. (13) over turn number n and combining with Eq. (12), the orbit variation due to beam energy change after n turns is:

$\Delta x = (x/E) \times \{ (E\_n - E_0) + (eV/\Delta\omega T_0) [\cos(\Delta\omega T_0 n + \phi_0 + \Delta\phi) - \cos(\phi_0 + \Delta\phi)] - nU_0 \}$. (14)

Equation (14) shows that orbit variation is a function of frequency change $\Delta\omega$ and phase change $\Delta\phi$. For the ideal model, this orbit variation is near zero. To correct frequency and phase errors, $\Delta\omega$ and $\Delta\phi$ can be adjusted to make Δx zero. To simplify, these corrections are performed separately.

In real machines, frequency error is usually small. To correct phase error first, we assume $\Delta\omega = 0$. Equation (14) then becomes:

$\Delta x \ = (xeV/E) \sin(\phi_0 + \Delta\phi)$, (15)

showing that the average horizontal beam position variation Δx is a sine function of RF phase change $\Delta\phi$. After three iterations of phase correction, the zero crossing is determined as the synchronous phase, as shown in Fig. 14 [Figure 14: see original paper]. To ensure at least 100 turns of beam transmission for subsequent frequency correction, a tune scan is performed by changing two quadrupole family strengths after the first phase correction.

For frequency correction, $\Delta\omega T_0$ can be treated as a small quantity. Equation (14) can be written as:

$\Delta x \ = (xeVn/E) [\cos(\phi_0 + \Delta\phi) + (\Delta\omega T_0/2) \sin(\phi_0 + \Delta\phi)] - (xnU_0/E)$, (16) where the average beam position variation Δx is a linear function of frequency change $\Delta\omega$. A line is fitted and the zero crossing is considered the synchronous frequency after three iterations, as shown in Fig. 15 [Figure 15: see original paper].

In RF correction, synchrotron motion must be considered. The number of evaluated turns should be significantly smaller than 304 turns for the HALF storage ring, related to the synchrotron frequency of 2.06 kHz. Therefore, the average position over 20 turns is used. The beam loss CDF is shown in Fig. 16 [Figure 16: see original paper]. The beam can survive more than 1000 turns and eventually become a stored beam. Table 7 shows beam transmission at each commissioning stage.

F. Beam-based alignment

This step performs closed orbit BBA to obtain the beam reference orbit, known as the golden orbit. CO BBA is similar to the method described in Section V.B. For the target quadrupole, the nearest BPM reading is taken as the beam position in that quadrupole. Using orbit correctors, the beam is moved to several different positions within the target quadrupole. At each position, changes in all BPM readings are recorded after varying the target quadrupole strength by ΔK. The orbit changes can be fitted as a linear function of beam position inside the target quadrupole. The zero-crossing point of the fitting function is least affected by changing the target quadrupole strength. By averaging zero-crossing points from all BPMs, the center of the target quadrupole is determined. The entire BBA routine repeats this process for all quadrupoles in both horizontal and vertical planes. To improve BBA accuracy, measurements are repeated after moving the beam to the reference orbit obtained from the previous BBA process. Recently, a novel BBA method based on a neural network (NN) was developed to determine the beam reference orbit in a storage ring [40]. The NN-based BBA is a good choice for the initial commissioning stage of a storage ring, where beam optics differ significantly from the ideal model and the closed orbit deviates from magnet centers. This method can be applied to real HALF storage ring commissioning in the future.

After performing CO BBA, the closed orbit is corrected to the reference orbit. The distribution of all corrector strengths after correcting the beam to the golden orbit is shown in Fig. 17 [Figure 17: see original paper] for 10 sets of random error seeds. Correcting the beam orbit to quadrupole centers is crucial for optics correction because off-axis beams in quadrupoles experience additional dipole fields (feed-down effects) that directly affect beam optics.

G. Optics correction

Linear optics is essential for storage ring operation, primarily including beta and dispersion functions [41]. Due to lattice errors, optics deviate from ideal values, causing betatron tune shifts, dynamic aperture reduction, etc. To correct linear optics, the commonly used LOCO (Linear Optics from Closed Orbit) technique is performed, which can restore storage ring periodicity, reduce negative effects of nonlinear resonances, and increase beam lifetime and DA [42, 43]. All quadrupoles are used for optics correction since they are independently powered. To correct coupling, skew quadrupoles combined with sextupole families SD1, SD2, and SF1 are used. Correction results for one error set are shown in Fig. 18 [Figure 18: see original paper] and Fig. 19 [Figure 19: see original paper]. The beta beating and dispersion deviation are greatly reduced to low levels. Lattice periodicity is restored, as shown in Fig. 20 [Figure 20: see original paper]. The betatron tunes are (0.193, 0.195), close to the ideal values (0.190, 0.190).

VI. PERFORMANCE AFTER CORRECTION

The start-to-end commissioning simulation is performed with 10 sets of random error seeds as mentioned in Section V.F. After complete correction, the optical function results are shown in Fig. 21 [Figure 21: see original paper] and Fig. 22 [Figure 22: see original paper]. The RMS beta beating is 1.4% and 0.86% in horizontal and vertical planes, respectively. The RMS horizontal dispersion deviation is 1.6 mm, and the RMS vertical dispersion deviation is 1.4 mm. The 6D dynamic aperture is close to the ideal case, as shown in Fig. 23 [Figure 23: see original paper]. On average, the DA area is restored to 75% of the design value after this simulated commissioning process. The average working point is (0.192, 0.194), close to the ideal value of (0.190, 0.190). For real commissioning, transverse tunes could be moved to different resonances to achieve round beam, which helps increase beam lifetime and suppress intra-beam scattering effects. To further improve dynamic performance, nonlinear optimization can be performed for the real machine through online experiments [44]. However, this procedure is not necessary for the simulated commissioning process.

VII. SUMMARY AND CONCLUSION

The start-to-end commissioning simulation for the HALF storage ring has been performed. For a storage ring without correction, the closed orbit is often absent, which is even more problematic in fourth-generation light sources where the beam cannot transmit through the first turn. Therefore, trajectory correction should be performed during initial commissioning. Simulation results demonstrate that this correction process is effective, enabling beam survival for more than 100 turns. By ramping sextupoles and correcting RF errors, the beam is successfully stored. Finally, the CO BBA and LOCO processes correct beam optics to the ideal model, greatly improving storage ring dynamic performance. The average DA area is restored to 75% of the ideal error-free value after the complete simulated commissioning process, demonstrating that the presented correction chain is effective and successful. The simulated commissioning significantly increases confidence for future real machine commissioning. Additionally, commissioning software will be developed based on this simulated commissioning process.

[1] S. Mobilio, F. Boscherini, and C. Meneghini, *Synchrotron Radiation: Basics, Methods and Applications* (Springer, 2015).
[2] D. H. Bilderback, P. Elleaume, and E. Weckert, Journal of Physics B: Atomic, Molecular and Optical Physics 38, S773 (2005).
[3] H.-J. Xu and Z.-T. Zhao, Nuclear Science and Techniques 19, 1 (2008).
[4] S.-Q. Tian, B.-C. Jiang, Q.-G. Zhou, Y.-B. Leng, and Z.-T. Zhao, Nuclear Science and Techniques 25, 010102 (2014).
[5] Y.-Y. Wang, L. Shang, F.-L. Shang, and Y.-M. Lu, Nuclear Science and Techniques 27, 2 (2016).
[6] D. Einfeld, M. Plesko, and J. Schaper, Journal of Synchrotron Radiation 21, 856 (2014).
[7] S. C. Leemann, S. Liu, A. Hexemer, M. A. Marcus, C. N. Melton, H. Nishimura, and C. Sun, Phys. Rev. Lett. 123, 194801 (2019).
[8] R. Hettel, Journal of Synchrotron Radiation 21, 843 (2014).
[9] M. Eriksson, J. F. van der Veen, and C. Quitmann, Journal of Synchrotron Radiation 21, 837 (2014).
[10] P. F. Tavares, S. C. Leemann, M. Sjöström, and Å. Andersson, Journal of Synchrotron Radiation 21, 862 (2014).
[11] C. Steier et al., in *Proceedings of IPAC' 17*, International Particle Accelerator Conference No. 8 (JACoW, Geneva, Switzerland, 2017) pp. 2824–2826.
[12] L. Liu, N. Milas, A. H. C. Mukai, X. R. Resende, and F. H. de Sá, Journal of Synchrotron Radiation 21, 904 (2014).
[13] J.C. Biasci, J.-F. Bouteille, N. Carmignani, J. Chavanne, D. Coulon, Y. Dabin, F. Ewald, L. Farvacque, L. Goirand, J. Jacob, G. Lebec, S. M. Liuzzo, B. Nash, M. Hahn, H. Pedroso-Marques, T. Perron, E. Plouviez, P. Raimondi, J. L. Revol, K. B. Scheidt, and V. Serrière, Synchrotron Radiation News 27, 12 (2014).
[14] M. Borland, T. Berenc, R. Lindberg, V. Sajaev, and Y. Sun, in *Proceedings of NAPAC' 16*, North American Particle Accelerator Conference No. 3 (JACoW, Geneva, Switzerland, 2017) pp. 4186–4188.
[15] Y. Jiao, G. Xu, X.-H. Cui, Z. Duan, Y. Guo, P. He, D. Ji, J. Li, X.-Y. Li, C. Meng, Y. Peng, T. Saike, J.-Q. Wang, N. Wang, Y.-Y. Wei, H. Xu, F. Yan, C.-H. Yu, Y.-L. Zhao, and Q. Qin, Journal of Synchrotron Radiation 25, 1611 (2018).
[16] Y.-M. Peng, J.-S. Cao, J.-H. Chen, H.-Y. Dong, P. He, Y. Jiao, L. Kang, W. Kang, J. Li, J.-Y. Li, G.-P. Lin, F. Liu, F.-L. Long, C. Meng, X. Qi, H.-M. Qu, Y.-F. Sui, S. Wang, G. Xu, Q. Ye, J. Zhang, P. Zhang, and W.-M. Pan, Nuclear Science and Techniques 35, 16 (2024).
[17] Y. Zhao, Y. Jiao, and S. Wang, Nuclear Science and Techniques 32, 71 (2021).
[18] Z. Zhao, B. Jiang, Y. Leng, S. Tian, L. Yin, and M. Zhang, in *Proceedings of IPAC' 15*, International Particle Accelerator Conference No. 6 (JACoW, Geneva, Switzerland, 2015) pp. 19–21.
[19] X.-Z. Liu, S.-Q. Tian, X. Wu, M. Wang, and Z.-T. Zhao, Nuclear Science and Techniques 32, 83 (2021).
[20] X. Wu, S. Tian, X. Liu, W. Zhang, and Z. Zhao, Nuclear Instruments and

Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1025, 166098 (2022).
[21] Z. Bai, G. Feng, T. He, W. Li, W. Li, G. Liu, Z. Ren, L. Wang, P. Yang, S. Zhang, and T. Zhang, in *Proceedings of IPAC' 21*, International Particle Accelerator Conference No. 12 (JACoW Publishing, Geneva, Switzerland, 2021) pp. 407–409.
[22] P.-H. Yang, G.-W. Liu, J.-H. Xu, W.-W. Li, T.-L. He, and Z.-H. Bai, Nuclear Science and Techniques 34, 107 (2023).
[23] H.-X. Yin, J.-B. Guan, S.-Q. Tian, and J.-K. Wang, Nuclear Science and Techniques 34, 147 (2023).
[24] W. Gao, L. Wang, and W. Li, Phys. Rev. ST Accel. Beams 14, 094001 (2011).
[25] D. Ji, X. Cui, Z. Duan, Y. Jiao, Y. Wei, and Y. Zhao, in *Proceedings of IPAC' 18*, International Particle Accelerator Conference No. 9 (JACoW Publishing, Geneva, Switzerland, 2018) pp. 4186–4188.
[26] D. Ji, B. Wang, and X. Cui, in *Proceedings of IPAC'23*, IPAC'23 - 14th International Particle Accelerator Conference No. 14 (JACoW Publishing, Geneva, Switzerland, 2023) pp. 2043–2045.
[27] K. Chen, Z. Wang, G. Wang, T. He, Z. Wang, M. Hosaka, D. He, and W. Xu, in *Proceedings of IPAC' 24*, IPAC' 24 - 15th International Particle Accelerator Conference No. 15 (JACoW Publishing, Geneva, Switzerland, 2024) pp. 2043–2045.
[28] T. Hellert, P. Amstutz, C. Steier, and M. Venturini, Phys. Rev. Accel. Beams 22, 100702 (2019).
[29] A. Terebilo, in *Proceedings of PACS2001*, Vol. 4 (2001) pp. 3203–3205 vol.4.
[30] Z.-H. Bai, G.-W. Liu, T.-L. He, W.-W. Li, P.-H. Yang, W.-M. Li, S.-C. Zhang, L. Wang, and G.-G. Feng, High Power Laser and Particle Beams 34, 104003 (2022).
[31] Z. Bai, G. Feng, T. He, W. Li, W. Li, G. Liu, L. Wang, P. Yang, and S. Zhang, in *Proceedings of IPAC' 23*, IPAC' 23 - 14th International Particle Accelerator Conference No. 14 (JACoW Publishing, Geneva, Switzerland, 2023) pp. 1075–1078.
[32] G. Liu, W. Li, L. Wang, and P. Wang, in *Proceedings of IPAC' 21*, International Particle Accelerator Conference No. 12 (JACoW Publishing, Geneva, Switzerland, 2021) pp. 2878–2880.
[33] W. Song, L. Shang, F. Shang, W. Liu, and Z. Sun, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 990, 164986 (2021).
[34] S. Liuzzo, N. Carmignani, L. Farvacque, and B. Nash, in *Proceedings of IPAC' 17*, International Particle Accelerator Conference No. 8 (JACoW, Geneva, Switzerland, 2017) pp. 3067–3069.
[35] G. Portmann, D. Robin, and L. Schachinger, in *Proceedings of Particle Accelerator Conference*, Vol. 4 (1995) pp. 2693–2695 vol.4.
[36] X. Huang, *Beam-based Correction and Optimization for Accelerators*, 1st ed. (CRC Press, Boca Raton, 2019).

[37] S.-W. Wang, W. Xu, X. Zhou, W.-B. Wu, B. Li, K. Xuan, and J.-Y. Li, Nuclear Science and Techniques 29, 176 (2018).
[38] S.-Y. Lee, *Accelerator Physics Fourth Edition* (World Scientific Publishing Company, 2018).
[39] V. Sajaev, Phys. Rev. Accel. Beams 22, 040102 (2019).
[40] G.-L. Wang, K.-M. Chen, S.-W. Wang, Z. Wang, T. He, M. Hosaka, G.-Y. Feng, and W. Xu, Nuclear Science and Techniques 35, 75 (2024).
[41] G. Liu, L. Wang, F. Wu, and K. Xuan, in *Proceedings of IPAC' 17*, International Particle Accelerator Conference No. 8 (JACoW, Geneva, Switzerland, 2017) pp. 727–729.
[42] J. Safranek, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 388, 27 (1997).
[43] G. J. Portmann, J. A. Safranek, and X. Huang, *MATLAB-BASED LOCO*, Tech. Rep. (SLAC National Accelerator Lab., Menlo Park, CA (United States), 2011).
[44] X. Huang and J. Safranek, Phys. Rev. ST Accel. Beams 18, 084001 (2015).

Note: Figure translations are in progress. See original paper for figures.