OPTIMIZATION AND UPDATE OF THE HALF STORAGE RING PHYSICS DESIGN

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Abstract

The Hefei Advanced Light Facility (HALF), a soft X-ray diffraction-limited storage ring light source at NSRL, began construction in 2023. This paper presents the optimization and update of the physics design for the HALF storage ring in the past two years.

INTRODUCTION

The Hefei Advanced Light Facility (HALF), shown in Fig. 1, is a soft X-ray diffraction-limited storage ring light source currently under construction in Hefei, China, with construction started in 2023 and scheduled for completion in 2028. The HALF storage ring, with a full-energy linac as its injector, consists of 20 identical cells, which employ a modified hybrid six-bend achromat (H6BA) lattice with both long and short straight sections [1, 2]. The natural emittance of the HALF storage ring is 85 pm·rad at an energy of 2.2 GeV, with the capability to be increased to 2.5 GeV. HALF will have approximately 35 beamlines in total, the vast majority of which are insertion device (ID) beamlines, and 10 ID beamlines will be constructed in the present Phase I. HALF has now entered the equipment installation phase. In the past two years, some optimizations and updates have been made to the physics design of the HALF storage ring, which will be presented in this paper.

Figure 1: Hefei Advanced Light Facility (HALF) currently under construction in Hefei, China.

LATTICE AND ERROR EFFECTS

All magnets of the HALF storage ring are electromagnets, with energy increase taken into account. For the combined-function reverse bends, before their installation, we slightly adjusted their quadrupole fields while keeping their dipole fields unchanged, which reduced the magnetic field saturation of one RB family and also helped increase the dynamic aperture (DA). Considering the adjustment of the RBs, through linear and nonlinear lattice optimization [3], the DA with RF cavity included was increased, and the amplitude-dependent tune shifts (ADTSs) were better controlled for beam injection in the full-coupling beam mode. This resulted in a new version (Version 2025) of the HALF storage ring lattice, shown in Fig. 2. Table 1 presents the main storage ring parameters, including the parameters with two damping wigglers (DWs), for both the 2.2 GeV and 2.5 GeV energies. To provide a safety margin for off-axis injection, we also designed an alternative lattice solution with a larger DA by moving the integer parts of betatron tunes from (48, 17) to (47, 18) [3].

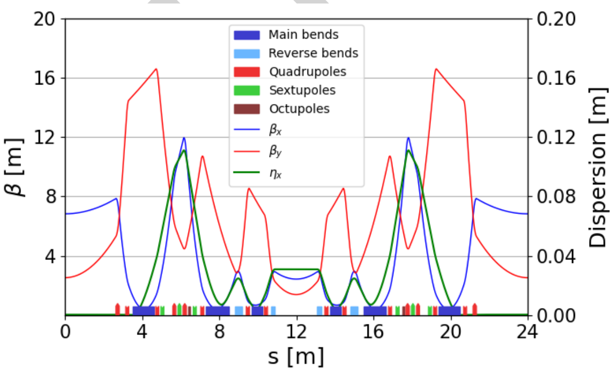

Figure 2: Modified H6BA lattice (Version 2025) of one cell of the HALF storage ring.

Table 1: Main Parameters of the HALF Storage Ring

Parameter	**2.2 GeV**	**2.5 GeV**
Circumference	479.86 m	
Straight sections	20 × 5.3 m + 20 × 2.2 m	
Natural emittance	85.4 pm·rad	110.3 pm·rad
Natural emittance w/DWs	71.9 pm·rad	92.8 pm·rad
Betatron tunes	48.21/17.21	
Natural chromaticities	-82.5/-59.6	
Momentum compaction	0.94×10^{-4}	
Natural damping times	28/39/24 ms	19/26/16 ms
Damping times w/DWs	22/27/16 ms	16/20/12 ms

For this new lattice version, with error effects considered, the DA with RF cavity included, as shown in the left plot of Fig. 3, is about 7 mm in the positive horizontal direction, from which the beam is injected. The 6D local momentum aperture (LMA) with error effects is shown in the right plot of Fig. 3. With a beam current of 400 mA and the bunch

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lengthened by a factor of 4, the Touschek lifetime considering error effects is nearly 8 hours for a 10%-coupling beam, and about 18 hours for a full-coupling beam.

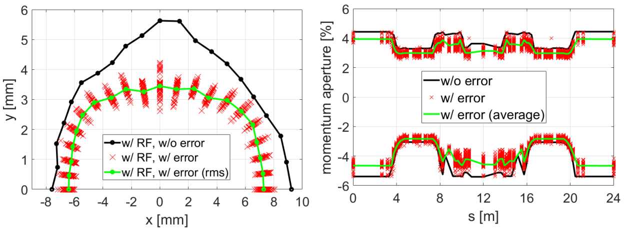

Figure 3: DA (left) and LMA (right) with RF cavity and errors included. The beam is injected from the positive horizontal direction of DA.

INJECTION AND FULL-COUPLING BEAM

The HALF storage ring adopts off-axis injection. The three-kicker (K1, K2, and K3) bump injection scheme with an anti-septum (K2) is employed during beam commissioning. For user operation, the nonlinear kicker (NLK) injection scheme is used instead, which enables transparent injection. Both injection schemes share a common septum, and their layouts are compatible within a long straight section, as illustrated in Fig. 4. Efforts have been made to reduce the strength of the septum's leakage field. The magnetic fields of the three kickers have been jointly measured and optimized to minimize the disturbance of the local bump orbit to the stored beam. The structure of the NLK has been optimized for off-axis transparent injection in the full-coupling beam operation mode to avoid beam loss on the NLK during injection.

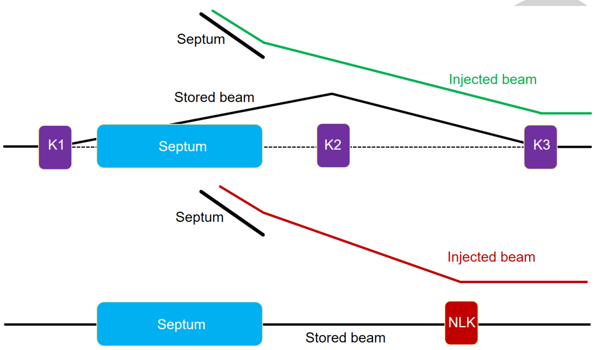

Figure 4: Layouts of two compatible injection schemes. Upper: three-kicker bump injection used for beam commissioning; Lower: NLK injection used for user operation.

IMPEDANCE AND BEAM INSTABILITIES

A systematic impedance modeling study for the HALF storage ring has established both narrow-band and broad-band impedance budgets through two computational campaigns [4]. Narrow-band trapped modes were characterized up to 20 GHz using particle swarm optimization fitting. Gate valves were identified as the dominant longitudinal impedance source (e.g., a 7.746 GHz mode contributes 114.1 kΩ in total), while in-vacuum undulators (IVUs) were found to be the most severe vertical impedance contributors, with ultra-low-frequency modes reaching transverse shunt impedances as high as 257 MΩ. Additionally, BPM-bellow blocks produce substantial cumulative effects in all planes. The broad-band budget, derived from short-range wake simulations with a 0.5 mm bunch, provides loss factors and kick factors for both the natural 2 mm bunch and a threefold stretched bunch, demonstrating that bunch lengthening by the harmonic cavity (HC) reduces the total loss factor by an order of magnitude and significantly lowers transverse kicks. Geometric wake potentials are comparable to resistive-wall wakes at short range and exhibit persistent oscillations due to high-frequency trapped modes, underscoring the importance of geometric impedance for single-bunch dynamics. These results pinpoint the critical impedance sources and will serve as the foundation for future mitigation measures (particularly for gate valves and IVUs) and comprehensive beam dynamics simulations to ensure stable operation of HALF.

Based on the latest impedance model, we have further investigated the collective instabilities. The combined effect of high-resistivity non-evaporable getter coating and coherent synchrotron radiation can lead to a microwave instability (MWI) threshold of about 0.2 mA without the HC. With the HC, the bunch length is expected to increase by a factor of at least 3 and up to 6, which raises the MWI threshold almost proportionally. Special attention has been paid to the optimization of trapped modes. However, gate valves, each with a shunt impedance on the order of kΩ, can still excite coupled-bunch instabilities if the bunch lengthening is insufficient. To suppress ion effects, a 90% filling pattern with uniformly distributed gaps (e.g., 4 or 10 bunch trains) is adopted. With the horizontal and vertical chromaticities corrected to (+5, +3), together with a bunch lengthening factor of at least 3, most transverse instabilities, including single-bunch and coupled-bunch modes, are suppressed, unless extremely strong transverse higher-order modes are present, which we specifically avoid during impedance optimization.

OTHER ASPECTS OF PHYSICS DESIGN

Collimation

To protect key devices from damage caused by beam loss, two horizontal collimators and one vertical collimator are placed in the downstream high-dispersion regions of the 1st, 11th, and 6th lattice cells, respectively. The horizontal collimators effectively intercept beam losses resulting from Touschek scattering. The vertical collimator further reduces beam loss at IDs due to Touschek scattering and beam–gas elastic scattering. With nominal apertures of ±5.5 mm for the two horizontal collimators and ±3.5 mm for the vertical collimator, the overall collimation efficiency exceeds 80%, considering various beam loss scenarios. With these collimators employed, the resulting beam lifetime reduction is less than 10%, and the DA remains acceptable for beam injection.

Insertion Device Compensation

In Phase I, 13 IDs, including two DWs, will be installed in the HALF storage ring. Some of these IDs have already been manufactured and are currently undergoing detailed magnetic field measurements with Hall probes. Kick maps are calculated from the measured data and compared with those obtained from the theoretical model. The measured and theoretical results are in good agreement. Figure 5 shows the comparison of kick maps obtained from the magnetic field measurement and theoretical model for HU115. Theoretical models are being used to generate the compensation feedforward tables for these IDs. The compensation methods mainly include current strip shimming and quadrupole feedforward compensation [5].

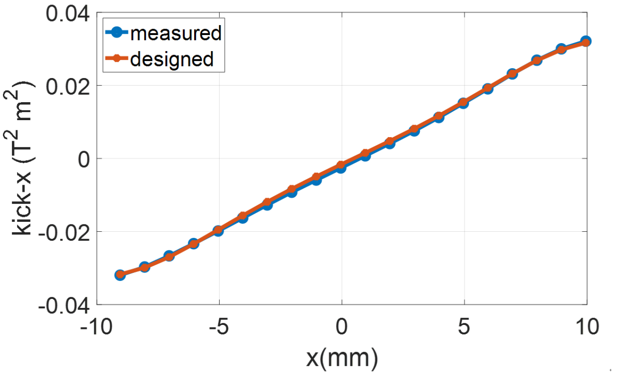

Figure 5: Comparison of kick maps obtained from the measurement and theoretical model for HU115.

Emittance Compensation

In the HALF storage ring, the ultra-low diffraction-limited emittance and reduced bend radiation loss can lead to considerable emittance variations from ID gap adjustments. A short variable-gap wiggler placed in a dispersive straight section is used to compensate for the emittance variations by utilizing the quantum excitation effect [6]. Despite being significantly shorter, it achieves emittance compensation comparable to the radiation-damping-based variable-gap DW scheme, while also yielding substantially smaller energy spread variations, resulting in very small effective emittance variations at short dispersive straight sections. Figure 6 presents the compensation of both the emittance at long dispersion-free straight sections and the effective emittance at short dispersive straight sections achieved with the short variable-gap wiggler.

Energy Increase

Increasing the beam energy from 2.2 GeV to 2.5 GeV not only mitigates the severe intra-beam scattering effect but also increases the radiation flux. It also reduces the emittance growth rate due to the installation of IDs in short dispersive straight sections, and is better for suppressing beam instabilities, reducing ID effects, and increasing beam lifetime.

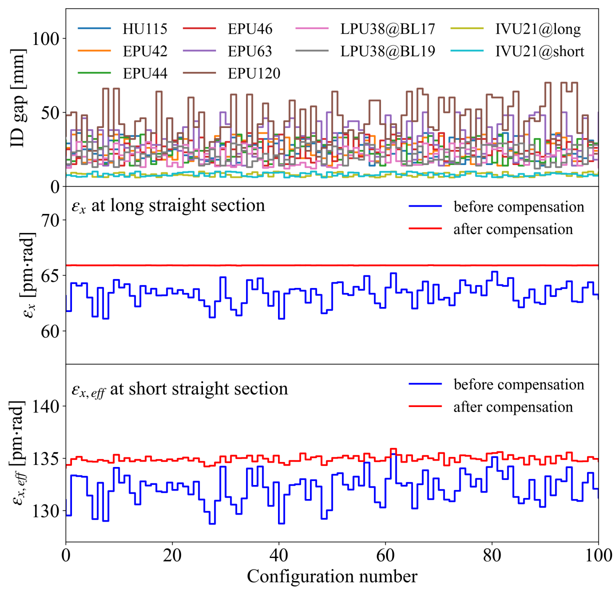

Figure 6: Compensation of both the emittance at long dispersion-free straight sections and the effective emittance at short dispersive straight sections.

CONCLUSION

HALF, a soft X-ray diffraction-limited storage ring light source, is currently under construction in China, and has now entered the equipment installation phase. The HALF storage ring was designed using a modified H6BA lattice with both long and short straight sections. Based on this lattice, the physics design of the HALF storage ring has been extensively studied and is now largely finalized. Comprehensive preparations for beam commissioning will soon begin.

ACKNOWLEDGMENTS

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