PROGRESS ON THE STORAGE RING PHYSICS DESIGN OF HEFEI ADVANCED LIGHT FACILITY (HALF)

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Abstract

The Hefei Advanced Light Facility (HALF) is a soft X-ray and VUV diffraction-limited storage ring to be built in the Hefei city of China. This paper reports the recent progress on the physics design of the HALF storage ring, including lattice modification and optimization, error and insertion device effects, collective effects, injection scheme and collimation.

INTRODUCTION

The Hefei Advanced Light Facility (HALF), a green-field diffraction-limited storage ring in the soft X-ray and VUV ranges, will be built in Hefei, China. The HALF concept was first proposed 15 years ago [1] by the National Synchrotron Radiation Laboratory (NSRL), which also operates the second-generation Hefei Light Source (HLS) [2]. The HALF project was approved more than a year ago and will be built at a new location nearly 20 km from the current HLS site. The HALF accelerator complex consists of a full-energy linac, a transfer line and a diffraction-limited storage ring.

The HALF storage ring was designed with the requirement of achieving a natural emittance of < 100 pm·rad and including 20 long straight sections. HALF proposed and used a modified hybrid six-bend-achromat (H6BA) lattice [3], which offers a relatively large dynamic aperture (DA) for off-axis injection and includes both a long and a short straight section in each lattice cell to accommodate more insertion devices (IDs). Based on this modified H6BA lattice, significant progress has been made in the storage ring physics design over the past two years.

DESIGN PROGRESS

Lattice Modification and Optimization

The HALF modified H6BA lattice [3] replaces the three combined-function bend unit cells of the original hybrid 7BA lattice [4] with two longitudinal gradient bend (LGB) and reverse bend (RB) unit cells and a mid-straight section. Compared to another modified H6BA lattice proposed by Diamond-II [5], this H6BA lattice has a superior ability to reduce both the emittance and damping times, due to the use of LGB/RB unit cells. This feature is crucial for HALF to achieve its emittance goal and suppress the intra-beam scattering (IBS) effect.

Compared to the previous lattice design [3], the current design has made three main changes: 1) reducing the bending angles of reverse bends, increasing momentum compaction factor; 2) using 3 slices to replace the 5 slices of the innermost LGB family; and 3) adding a family of thin sextupoles close to the first RB family. Figure 1 shows the current HALF lattice, with the storage ring parameters listed in Table 1. The natural emittance is 85.8 pm·rad, and full-coupling beam is adopted. The long straight section is 5.3 m long, and the mid-straight is 2.2 m long. The maximum strength of quadrupoles is about 50 T/m.

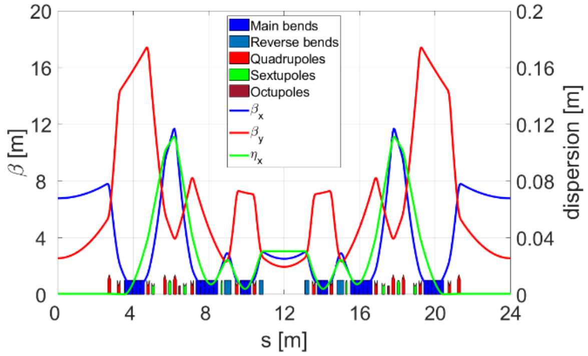

Figure 1: Magnet layout and linear optics of a cell of the HALF modified H6BA lattice.

Table 1: Main Parameters of the HALF Storage Ring

Parameter	Value
Energy	2.2 GeV
Circumference	479.86 m
Number of cells	20
Natural emittance	85.8 pm·rad
Betatron tunes (H/V)	48.19/17.19
Natural chromaticities (H/V)	-81.6/-56.6
Momentum compaction factor	0.94×10^{-4}
Damping partition (H/V/L)	1.36/1.0/1.64
Natural damping times (H/V/L)	28.5/38.8/23.7 ms
Natural energy spread	0.61×10^{-3}
Energy loss per turn	181.4 keV
Total absolute bending angle	438.6°

Four families of sextupoles and a family of octupoles were used. The thin sextupole family is mainly used for controlling amplitude dependent tune shifts (ADTS). In the full-coupling operation, the fractional tunes of off-axis injected beam with large horizontal amplitude should be separated to avoid losing the injected beam on the IDs with small vertical gaps. The introduction of the thin sextupoles was inspired by the IDB-MBA lattice [6], and there is a rough –*I* for nonlinear cancellation between two thin sextupoles across a long straight section. The thin sextupoles are also used as correctors. The chromaticities were corrected to (3, 3). Figure 2 shows the frequency map analysis of DA. Figure 3 shows the tune shifts with horizontal amplitude and momentum. The off-momentum tunes do not cross half-integer resonance lines within relative momentum deviations of ±3.5%.

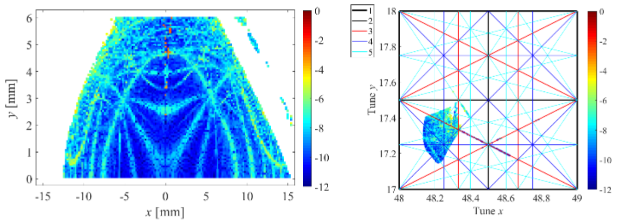

Figure 2: Frequency map analysis of on-momentum DA, with the colour bar denoting diffusion rate.

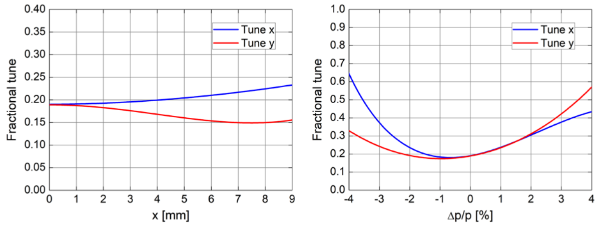

Figure 3: Tune shifts with horizontal amplitude (left) and momentum (right).

Error and Correction

Inevitable imperfections, including magnet misalignments, field errors and calibration errors, will lead to orbit and optics distortions and degeneration of nonlinear dynamics performance. Effects on beam dynamics from various errors were evaluated to check the robustness of the HALF lattice. Considering the error tolerance and the hardware costs, error budgets for the HALF storage ring were obtained [7]. Simulation results show that misalignments of quadrupoles are the main source of orbit distortions for HALF and magnet orientation errors will cause obvious beta-beatings and tune shifts.

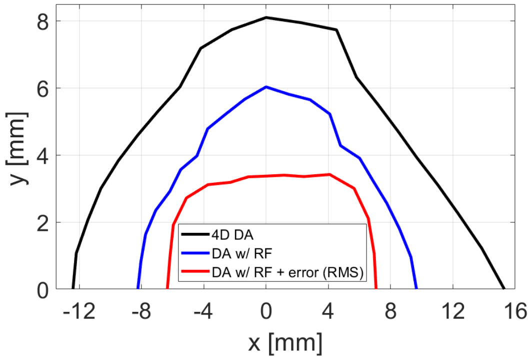

Figure 4: RMS 6D DA with errors (red), as well as the 4D (black) and 6D (blue) DAs without error. Beam is injected from +*x* plane.

To recover the good performance of HALF as much as possible, careful corrections for closed orbits, linear optics and transverse coupling were carried out. Detailed correction scheme can be found in Ref. [7]. After the corrections, the orbit distortions are limited within 60 μm (RMS value, the same below), the beta-beatings smaller than 1.1% and vertical dispersion lower than 1 mm. The natural emittance growth caused by errors is generally lower than 3%. Considering the error effect, the horizontal 6D DA is larger than 6 mm in the positive direction (direction of beam injection) as shown in Fig. 4, and the Touschek lifetime is longer than 5 hours for 10%-coupling beam with bunch lengthening.

Insertion Device Effect

The parameters of IDs were designed and optimized for the ten beam lines to be constructed in the first stage of the HALF project. The effects of the IDs on the storage ring were carefully analyzed with the kick-map method. It was found that the IDs can cause serious tune shifts and beta-beatings, and reduce the DA due to the nonlinear magnetic field of the EPUs. The linear parameters can be corrected by the four families of quadrupoles nearby. After the compensation, the tune shifts are very small, and the beta-beatings are less than 1% in both planes. To compensate the dynamic field integrals of the EPUs, an active shimming method with current strips was adopted to minimize the undesirable nonlinear dynamics effect [8]. With the ten IDs and two damping wigglers included (all gaps closed), the energy loss per turn becomes ~390 keV, and the natural emittance is reduced to ~58 pm·rad.

Collective Effects

Because of the relatively low beam energy and large machine circumference, the HALF storage ring has relatively long damping times. In order to suppress the emittance diluting effects caused by the IBS effect and other potential beam instabilities, two damping wigglers and a passive superconducting 3rd-harmonic cavity will be employed. Figure 5 shows the IBS induced emittance and energy spread increase, where full-coupling bunch is lengthened by a fac-tor of 4 and two damping wigglers are employed. The IBS effect is very serious in the HALF ring. The horizontal emittance with IBS is 68 pm·rad for a bunch charge of 1 nC, as shown in Fig. 5, and it is 153 pm·rad for 10%-cou-pling bunch.

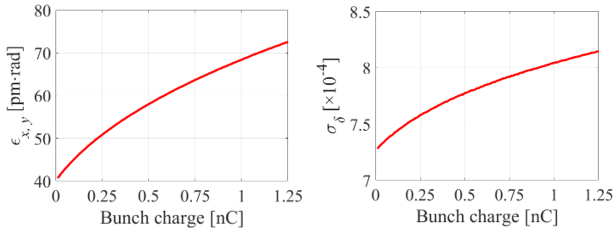

Figure 5: Increase of emittance (left) and energy spread (right) due to IBS.

A multi-bunch tracking Matlab code named STABLE was developed with the use of graphics-processing-unit acceleration technique [9]. At present, it can be used to study longitudinal beam dynamics considering arbitrary fill pattern, passive harmonic cavity, higher-order modes and arbitrary short-range wake. In the previous study of bunch lengthening for the HALF ring, we have shown that a small R/Q of < 45 Ω for harmonic cavity is necessary to obtain longer bunch lengthening without periodic transient beam loading effect at a high beam current [10].

The impedance budget is still under construction for the vacuum chambers including both resistive-wall and geometric components, modelled using ImpedanceWake2D and CST, respectively. The CSR impedance is also calculated. With RMS bunch length of 2 mm, the total longitudinal loss factor is 36.5 V/pC, and the transverse kick factors are 7980 and 6460 V/m/pC in the x and y planes, respectively. The impedance driven collective instabilities were simulated using ELEGANT and STABLE. With and without harmonic cavity, the longitudinal microwave instability threshold are 1.5 and 0.5 mA, respectively. The threshold of transverse single-bunch instabilities is higher than 10 nC with corrected chromaticities of (3, 3) and harmonic cavity.

Studies of coupled-bunch instabilities are also ongoing. HOM damper has been carefully designed and optimized to damp the HOMs of the superconducting cavities. The growth rate of long range resistive-wall instability at zero chromaticity is about 1300 s^{-1}. Considering the fill pattern of 8 bunch trains and 640 bunches in total and CO gas with pressure of 1 nTorr, the growth time of fast ion instability is about 0.2 ms. Transverse feedback system with damping time of at least 0.1 ms is needed to damp the instabilities.

Injection scheme

The injection scheme applied to the HALF storage ring employs a septum and a three-kicker bump. One of the kickers is specially designed as an anti-septum, which can deflect the stored beam without affecting the injection beam [11]. The layout parameters of the injection scheme is shown in Fig. 6. Because the blade of the anti-septum is only about 1 mm, the required dynamic aperture for the injection can be reduced to about 3.8 mm. The impact on the stored beam during the injection depends on the magnetic field consistency of the three kickers. According to the tracking analysis, the error of the bump should be controlled within 100 μm/μrad to minimize the perturbation to the stored beam. The prototype of the anti-septum as well as the other two kickers are under development. More detailed studies are being carried out to clarify the error tolerances for the injection system. For the details of this injection scheme and simulation, see Ref. [12].

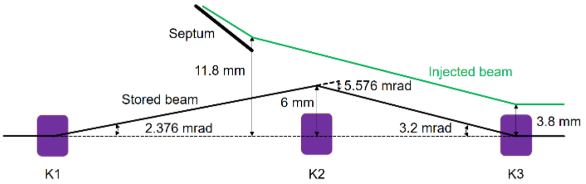

Figure 6: Layout parameters of the three-kicker bump injection scheme with an anti-septum (K2).

Collimation

The lifetime of the stored electron beam in the HALF storage ring is estimated to be 1 hour or so for the worst case. Thus the beam loss rate is much higher than third-generation light sources. Among different beam loss mechanisms, the most important one is the Touschek scattering. The Touschek beam loss happens almost constantly or without evident time structure. One should carefully treat the lost electrons to protect the IDs that usually have small gaps and are vulnerable to irradiation damage, and also the radiation shielding of the tunnel. Another important beam loss is the beam dumping due to intentional machine operation or important hardware failures that happen mostly in the storage ring but may also in the frontends of the beamlines. In this case, due to very small beam size of the stored beam and the instantly high loss rate, the beam may cause damage to the devices that receive the beam during the dumping process. A beam collimation system in the storage ring to mitigate the above effects is under design.

The total stored beam energy in the storage ring is modest compared to other fourth-generation light sources. The preliminary design of the collimation system envisions two collimators in the opposite arcs of the ring, with one (denoted as Coll.#1) in the first cell designed for beam injection, and the other (denoted as Coll.#2) in the 11th cell. Coll.#1 is placed close to the first dispersion peak of the arc section where it has a better opportunity to collect the particles with very large momentum deviation due to the Touschek scattering or the total beam with RF-off during beam dumping. Coll.#2 is placed close to the second dispersion peak in order to avoid confliction with the beamline from the undulator in the upstream long straight section. A longitudinal space of about 0.35 m is reserved for both Coll.#1 and Coll.#2 for the need of the hardware installation and local shielding. The design goal is to have about 70% collimation efficiency for Touschek losses and more than 50% for the dumping beam. The other beam loss scenarios will be included in the optimization of the collimation system.

CONCLUSION

The HALF project, a new soft X-ray and VUV diffraction-limited storage ring, has been approved and will be constructed at a new location of Hefei as one part of NSRL. Recently, we have made significant progress in the physics design of the HALF storage ring based on a modified H6BA lattice, which provides a long and a short straight section in each lattice cell. Further physics design is ongoing, mainly including lattice optimization, consideration of realistic magnet fields, further compensation of ID effect, establishment of the impedance budget of the whole ring and detailed study of injection.

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