NONLINEAR OPTIMIZATION OF THE HALF STORAGE RING LATTICE

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Abstract

The Hefei Advanced Light Facility (HALF) is a 4th-generation storage ring light source currently under construction in Hefei, China. Its storage ring utilizes a modified hybrid 6BA lattice. The HALF storage ring employs off-axis injection and is planned to operate in a full-coupling mode, which requires a large dynamic aperture and control of amplitude-dependent tune shifts. This paper presents the optimization of the nonlinear dynamics for the HALF storage ring, introducing a new version of the lattice and an alternative lattice solution featuring a larger dynamic aperture.

INTRODUCTION

The Hefei Advanced Light Facility (HALF), a diffraction-limited storage ring, is currently under construction in Hefei, China. The HALF storage ring consists of 20 modified hybrid six-bend achromat (H6BA) lattice cells, providing 20 long straight sections (LSS) and 20 medium straight sections (MSS) [1, 2]. With a circumference of 479.86 m, the lattice achieves a natural emittance of 85 pm·rad at a beam energy of 2.2 GeV. All magnets in the storage ring are electromagnetic, allowing for flexible adjustment of strengths. This design not only preserves the option to increase the beam energy to 2.5 GeV but also provides considerable flexibility for lattice optimization. Although the main magnet layout and magnet designs have been finalized, the optimization of the linear optics and nonlinear dynamics continues. This paper reports the latest results on nonlinear dynamics optimization for the HALF lattice.

OPTIMIZATION MOTIVATION AND METHOD

The primary motivation for the nonlinear optimization of the HALF lattice is to control the amplitude-dependent tune shifts (ADTS), which are critical for injection. The working point of the HALF storage ring is on the linear difference resonance $\nu_x - \nu_y$, which can enhance the horizontal-vertical coupling, thereby increasing the beam volume and mitigating the intra-beam scattering (IBS) and Touschek scattering. However, this coupling complicates the off-axis injection, where the bunch is injected with a horizontal offset of approximately +6 mm. The large horizontal amplitude can couple into the vertical plane, potentially causing beam loss. Therefore, controlling ADTS is essential to keep the injected beam away from the coupling resonance. Earlier designs provided preliminary ADTS control; however, recent detailed tracking simulations revealed that the injection efficiency remains limited by coupling. Hence, further improvement of the nonlinear dynamics for the HALF lattice is required.

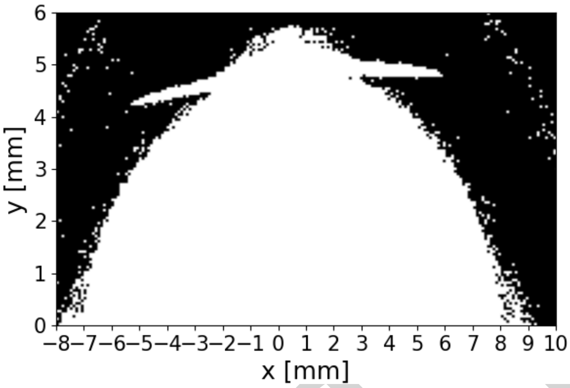

Figure 1: DA of the HALF V2024 lattice. The tracking was performed using Accelerator Toolbox [4] over 1000 turns.

In addition to ADTS control, the dynamic aperture (DA) with RF also requires improvement. Previous result presented a DA of approximately 9 mm for the HALF V2024 lattice [3], yet detailed analysis revealed an unstable region between $x = 8$ and 9 mm where particle survival is scattered. This reduces the usable DA to only about 8 mm, as shown in Fig. 1. Achieving a larger DA is therefore another key optimization goal.

Given that the HALF lattice offers few nonlinear knobs, the nonlinear optimization necessitates including quadrupole strengths as variables. In addition, HALF employs offset quadrupoles for reverse bends (RBs), allowing their quadrupole strengths to be adjusted while maintaining their dipole fields, until the offsets are fixed for installation. Furthermore, since magnet designs are already finalized, all optimizations must respect physical limits on magnet strengths.

To address the requirements above, the optimization was conducted in two stages. The first stage employed an analytical method for DA optimization and ADTS control. Reducing ring-averaged resonance driving terms (RDTs) is very effective in improving DA [5, 6], and the first-order ADTS can also be derived from driving terms. The efficiency of the analytical method enabled rapid optimization and exploration of various constraint settings. Many good solutions were obtained in this stage, with DA exceeding 8 mm and well-controlled ADTS. However, the analytical method provides indirect optimization of the actual tracking performance. In the second stage, where marginal gains in DA become important, a careful balance between DA details, ADTS, and other parameters is required. Therefore, based on the results from the first stage, the second stage performed a tracking-based optimization to enlarge the DA in the injection direction and control the tracked ADTS.

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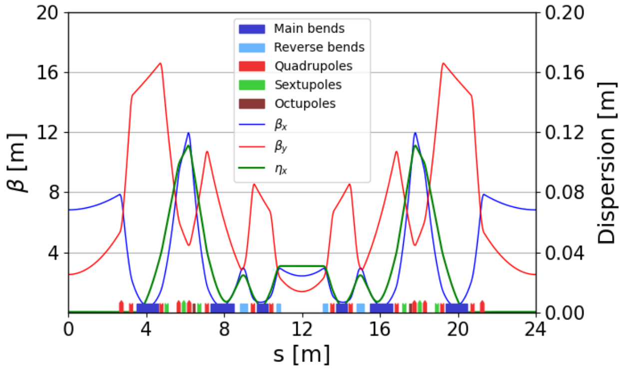

Figure 2: Linear optical functions and magnet layout of the HALF V2025 lattice.

Following the optimization strategy above, a new nominal lattice (V2025) was developed, along with an alternative lattice featuring an obviously enlarged DA.

NEW VERSION NOMINAL LATTICE

Figure 2 shows the linear optics of the HALF V2025 lattice. In the optimization, some constraints were set to prevent degradation of key linear optics parameters. Consequently, most parameters remain similar to those of V2024. Table 1 lists several main changes. The significant reduction in β_y at the midpoint of the MSS is particularly worth noting, as it not only benefits brightness but also mitigates the impact of vertical trapped-mode impedance from in-vacuum undulators (IVUs).

Table 1: Main Changes in Storage Ring Parameters.

Parameter	**V2024**	**V2025**
Natural emittance [pm]	85.9	85.4
Betatron tunes (H/V)	48.15/17.15	48.21/17.21
$\beta_{x,y}$@LSS [m]	6.7, 2.6	6.8, 2.5
$\beta_{x,y}$@MSS [m]	2.6, 2.0	2.4, 1.4
Nat. chromaticities (H/V)	-80.7/-56.4	-82.5/-59.6

Regarding nonlinear dynamics, the V2025 lattice demonstrates comprehensive improvements. As shown in Fig. 3, the DA reaches approximately 9 mm in the injection direction and exhibits a more uniform boundary compared to the V2024 lattice. Furthermore, the ADTS are well controlled, as shown in Fig. 4. Specifically, at $x = 6$ mm, the tune difference $\Delta\nu = \nu_x - \nu_y$ increases from 0.044 to 0.070, effectively suppressing horizontal-vertical coupling of the injected bunch. Additionally, the enhanced focusing also leads to a slight increase in the local momentum aperture (LMA) at dispersion bumps. Figure 5 shows LMA along the V2025 lattice cell.

AN ALTERNATIVE LATTICE WITH A NEW WORKING POINT

The previous paper demonstrated that a different working point can achieve a larger DA [3]. Here we also designed an alternative lattice with a different working point and a larger DA compared to the V2025 lattice. The RB parameters in the alternative lattice are the same as those in the nominal lattice.

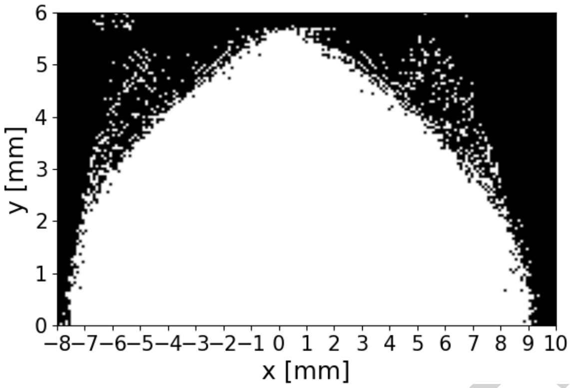

Figure 3: DA of the HALF V2025 lattice.

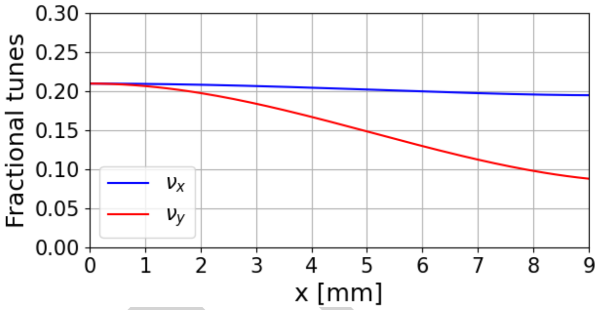

Figure 4: Amplitude-dependent tune shifts of the HALF V2025 lattice.

Figure 6 shows the linear optics of the alternative lattice, with the main storage ring parameters listed in Table 2. The integer tunes are adjusted to (47, 18). Reducing the horizontal tune relaxes the focusing, providing better potential for nonlinear dynamics optimization. Increasing the vertical tune achieves a lower β_y at the LSS. Although the natural emittance increases, the radiation brightness remains almost the same. This alternative lattice achieves a large DA of about 11 mm in the injection direction, as shown in Fig. 7. However, as shown in Fig. 8, it is more challenging to control ADTS in this lattice. Another disadvantage of the alternative lattice is a smaller LMA of approximately 2.5% at the dispersion bumps. Nevertheless, the lattice can serve as an alternative for low-coupling operation.

Furthermore, all sextupoles in the HALF storage ring are independently powered, while octupoles are partially inde-

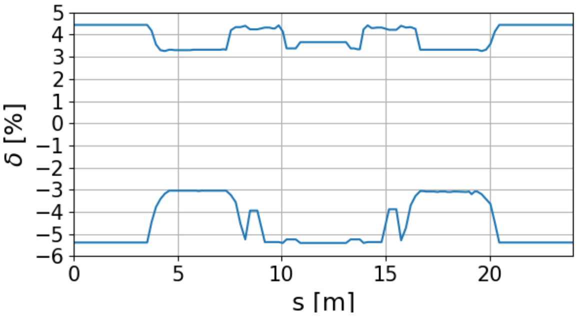

Figure 5: LMA of the HALF V2025 lattice.

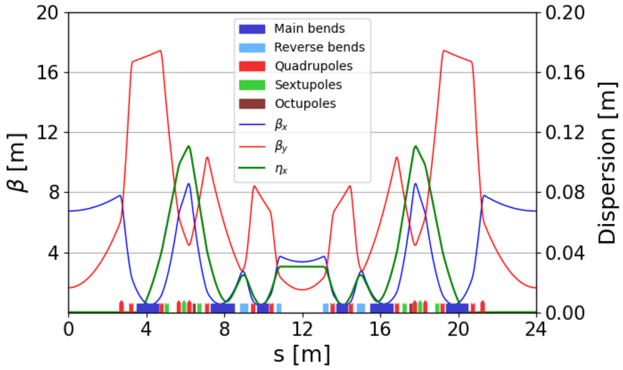

Figure 6: Linear optics of the alternative HALF lattice.

Table 2: Main Parameters of the Alternative Lattice.

Parameter	values
Natural emittance [pm]	92.7
Betatron tunes (H/V)	47.22/18.22
$\beta_{x,y}$@LSS [m]	6.7,1.6
$\beta_{x,y}$@MSS [m]	3.4,1.5
Natural chromaticities (H/V)	-70.9/-63.4

pendently powered. This hardware flexibility allows us to break the nonlinear lattice periodicity, providing more nonlinear knobs for tune shift control. Specifically, we examined a configuration in which sextupoles are grouped into 12 families and octupoles into 2 families. With this configuration, $\Delta\nu$ at $x = 6$ mm can be increased to 0.067, though at the cost of a reduced DA, as shown in Fig. 9. Depending on operational requirements for coupling and DA, a trade-off can be made through such grouping optimization.

CONCLUSION

An improved nominal lattice (V2025) and a large-DA alternative lattice were developed for the HALF storage ring. The HALF V2025 lattice achieves a DA of approximately 9 mm in the injection direction with well-controlled ADTS. It maintains a low natural emittance of 85.4 pm·rad and features a lower β_y at the MSS compared to the previous design. Additionally, the alternative lattice, operating at a different working point, offers a substantially larger DA. Through sextupole and octupole grouping optimization, this alternative can be configured to balance between DA and ADTS control.

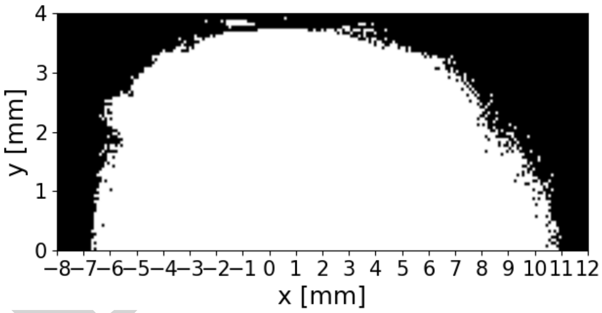

Figure 7: DA of the alternative HALF lattice.

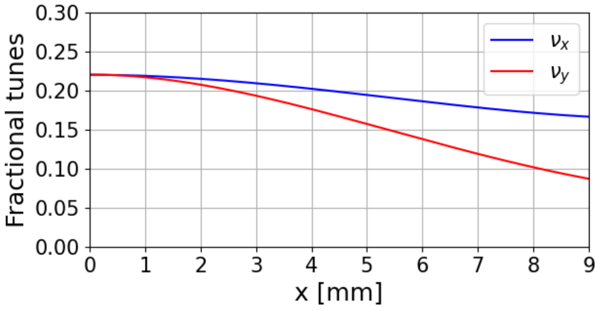

Figure 8: Amplitude-dependent tune shifts of the alternative HALF lattice.

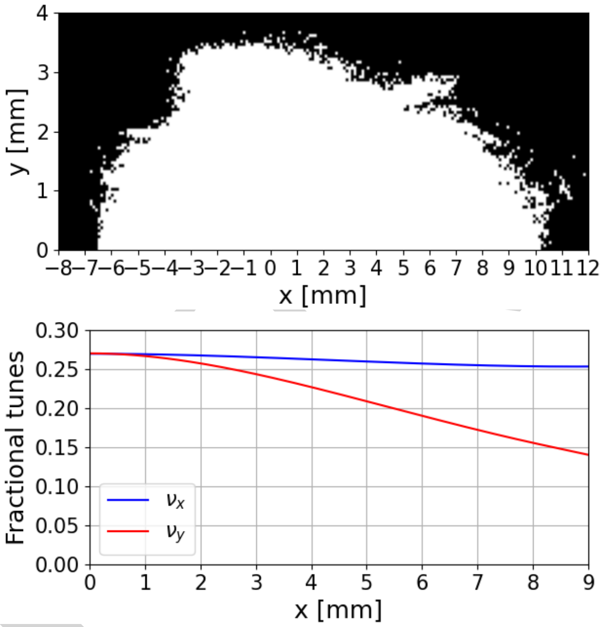

Figure 9: DA (top) and ADTS (bottom) of the alternative HALF lattice with grouped nonlinear magnets.

ACKNOWLEDGMENTS

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