ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL077

DDBA-H6BA LATTICE FOR THE NANOMETER-EMITTANCE DESIGN OF HEFEI LIGHT SOURCE

Penghui Yang*, Zhenghe Bai†, Zhiliang Ren, Lin Wang
National Synchrotron Radiation Laboratory, USTC, Hefei, China

Abstract

Recently, a double-double bend achromat (DDBA) lattice is designed for Hefei Light Source (HLS), a second-generation synchrotron radiation light source, which reduced the natural emittance a lot. In this paper, to further reduce the emittance and improve the brightness, a DDBA-hybrid 6BA lattice is proposed and applied to the design for the potential HLS upgrade. With more bending magnets, the emittance is significantly reduced from 36.4 nm·rad to 1.8 nm·rad at the cost of two short straight sections. After nonlinear dynamics optimization, the dynamic aperture and momentum aperture are large enough for the requirements from beam injection and lifetime.

INTRODUCTION

Hefei Light Source (HLS), dedicated to providing vacuum ultraviolet and soft X-ray synchrotron radiation, is a second-generation light source located at NSRL [1]. The beam energy is 800 MeV and the circumference of the storage ring is 66.13 m. At present, the HLS storage ring consists of four double-bend achromat (DBA) lattice cells with a natural emittance of 36.4 nm·rad, and each cell has a long straight section of 4 m and a short straight section of 2.3 m. Up to now, HLS has worked well for over 30 years and some efforts were also made to improve the performance, including enhancing the beam current from 300 mA to 400 mA, implementing top-off operation and increasing the bunch length using the harmonic cavity, etc.

To keep the competitiveness of HLS and further improve its performance, it is a good choice to significantly reduce the emittance and then enhance the brightness in the future. A very effective method to reduce beam emittance is to increase the number of bend magnets. As done with many third-generation light sources, MBA lattices were widely used in their upgrades [2–4] and such upgrades can also be considered for second-generation light sources like HLS. Inspired by the DDBA lattice proposed by Diamond [5], we have designed two DDBA lattices for HLS, which have emittances of about 4~5 nm·rad and with the straight sections unchanged [6]. To further reduce the emittance and increase the brightness, in this paper, the DDBA lattice and MBA lattice are combined and a DDBA-hybrid 6BA lattice is designed for HLS. The beam energy, circumference and length of each lattice cell will keep unchanged. And the nonlinear dynamics performance should also satisfy the requirements from injection efficiency and lifetime.

* penghui1@ustc.edu.cn
† baizhe@ustc.edu.cn

LATTICE DESIGN

Some considerations for the HLS storage ring designed with the DDBA-H6BA lattice will be first introduced, and then linear optics and nonlinear dynamics optimizations will be presented.

Lattice Considerations

The DDBA-H6BA lattice is also inspired by the DDBA lattice. The H6BA lattice can be treated as a product of the DDBA lattice by replacing the short straight section with two bending cells. Compared to the DDBA lattice, it has more bending magnets and then a lower emittance but fewer straight sections. Considering that the present HLS storage ring consists of four lattice cells with lengths of 16.53 m, to keep the positions of long straight sections unchanged, the upgrade storage ring will also has four lattice cells with the same length, that is two DDBA lattice cells and two H6BA lattice cells. The lengths of long and short straight sections are also 4.0 m and 2.3 m, respectively. If half of the DDBA and H6BA lattice are denoted as C_1 and C_2, respectively, the storage ring can be made with $C_1C_1 - C_2C_2 - C_1C_1 - C_2C_2$ and also with $C_1C_2C_2C_1 - C_1C_2C_2C_1$. Then this storage ring will have two periods, and the magnet layout of each period is shown in Fig. 1. To further reduce the emittance, reverse bends and longitudinal gradient bends [7] are employed. Besides, for compactness, one focusing quadrupole and one defocusing sextupole are removed, compared to the typical DDBA lattice cell.

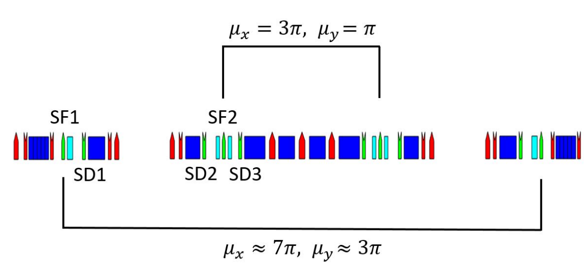

Figure 1: Magnet layout of one period of the DDBA-H6BA lattice. In the magnet layout, bends are in blue and cyan (RBs), quadrupoles in red and sextupoles in green.

To reduce the nonlinear perturbations from sextupoles, the transverse phase advances between SF2 are set to about $(3\pi, \pi)$, so that $-I$ transformation can be achieved between the sextupole families in H6BA lattice cells. Besides, the phase advances between SF1 in each period can be adjusted to about $(7\pi, 3\pi)$, so that $-I$ transformation can also be approximatively achieved between the sextupole families in DDBA lattice cells. In consideration of these settings,

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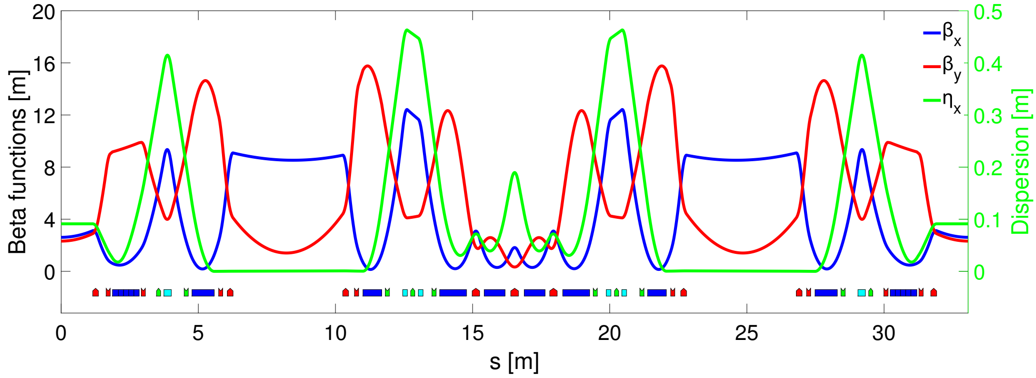

Figure 2: Linear optical functions of the DDBA-H6BA lattice.

the horizontal and vertical tunes of this storage ring can be 8.5~8.9 and 3.1~3.9, respectively. After several attempts, (8.58, 3.16) seems to be a better choice, in view of keeping away from the resonance line and making for good nonlinear dynamics performance.

Linear Optics Design

During optimizing the linear optics using the evolutionary algorithm, as mentioned above, some constraints should be satisfied, including the constraints for phase advances between sextupoles, the transverse tunes and the achromat condition in long straight sections. Besides, the dispersion in the short straight is limited to be lower than 0.1 m. The length of each lattice cell is strictly 16.53 m, while there is no limit on the bending angle of each cell. In the linear optics design, nonlinear dynamics indicators, including integrated strengths of sextupoles and natural chromaticities, are optimized, which is beneficial to the following nonlinear dynamics optimization [8, 9].

Figure 2 shows the linear optical functions of one selected solution after optimization which has a natural emittance of 1.8 nm·rad. The peak field of the LGB in the DBA lattice cell is 1.23 T, which is nearly the same as the dipole field of the bends in the present HLS storage ring. The dipole fields of combined-function bends in this lattice are 0.9~1.5 T and the quadrupole gradients of them are -2.3~-7.2 T/m. The dipole fields of three families of RBs are about -0.42 T~-0.34 T and their quadrupole gradients are about 12~15 T/m. The maximum strength of quadrupoles in the middle part of H6BA lattice cell is about 29 T/m and 18 T/m for other quadrupoles.

The main parameters of the storage ring designed with this DDBA-H6BA lattice (Case 1) and the HLS storage ring designed with the DBA lattice (Case 2) are listed in Table 1. The natural emittance is reduced by about 95% from 36.4 nm·rad to 1.8 nm·rad. The beta functions in long and short straight sections are also decreased, which is good for improving the radiation brightness from insertion devices (IDs). Due to the employment of RBs and more bends, the momentum compaction factor is reduced to 2.7×10^{-3} and this will result in a shorter bunch length and then probably more serious intra-beam scattering (IBS) effect and Touschek scattering effect. For the present HLS, the RF cavity has a peak voltage of 250 kV and a frequency of 204 MHz. The bunch length can be increased by about a factor of 2.4 with the harmonic cavity. The beam current is 400 mA filled within 45 buckets. With these conditions, the horizontal equilibrium emittances with the IBS effect included of the storage ring designed with DDBA-H6BA lattice are 2.38 nm·rad and 2.17 nm·rad for 5% and 10% transverse coupling, respectively. Compared to the present HLS storage ring, the brightness of vacuum ultraviolet and soft X-ray synchrotron radiation is increased by more than one order of magnitude.

Table 1: Main Parameters of the Storage Ring Designed with the DDBA-H6BA Lattice (Case 1) and the DBA Lattice (Case 2) for HLS

Parameter	Case 1	Case 2
Beam energy (MeV)	800	
Circumference (m)	66.13	
Nat. emittance (nm·rad)	1.8	36.4
Tansverse tunes	8.585/3.16	4.41/3.21
Nat. chromaticities	-20.0/-9.5	-9.9/-4.7
Mom. compaction	2.7×10^{-3}	2.1×10^{-2}
Energy spread	5.9×10^{-4}	4.7×10^{-4}
Damping times (ms)	12/22/19	20/21/11
Radiation loss (keV/turn)	16.2	16.7
β_x and β_y at long straight sections (m)	8.6/1.4	15.9/3.4
β_x and β_y at short straight sections (m)	2.7/2.3	3.1/2.1

Nonlinear Dynamics Optimization

Nonlinear dynamics performance is optimized with five families of sextupoles using a multi-objective particle swarm optimization algorithm. The objective functions include the areas of on-momentum dynamic aperture (DA) and off-momentum DA, tracked at the center of the long straight section. With chromaticities corrected to (+2, +2), the optimized DAs are shown in Fig. 3, and Fig. 4 shows the frequency map analysis (FMA). The on-momentum DAs (with-

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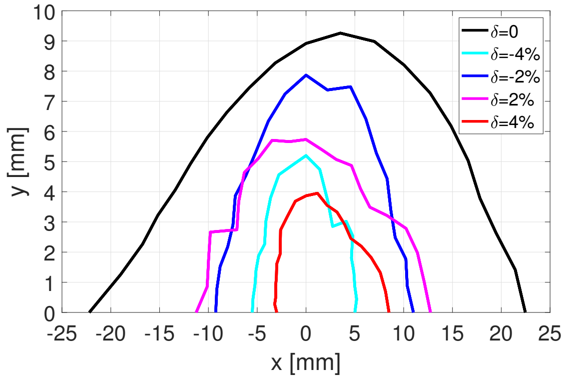

Figure 3: On-momentum and off-momentum DAs after non-linear dynamics optimization, tracked at the center of the long straight section.

out error) in the horizontal and vertical planes are about 22 mm and 9 mm, respectively. FMA shows that an eighth-order resonance line, 6x+2y=58, will cause a distinct unstable motion, which may limit the horizontal DA within about 15 mm. Figure 5 shows the momentum-dependent tune footprints and we can see that the tune shifts with momentum deviations of ±4% are less than ±0.1.

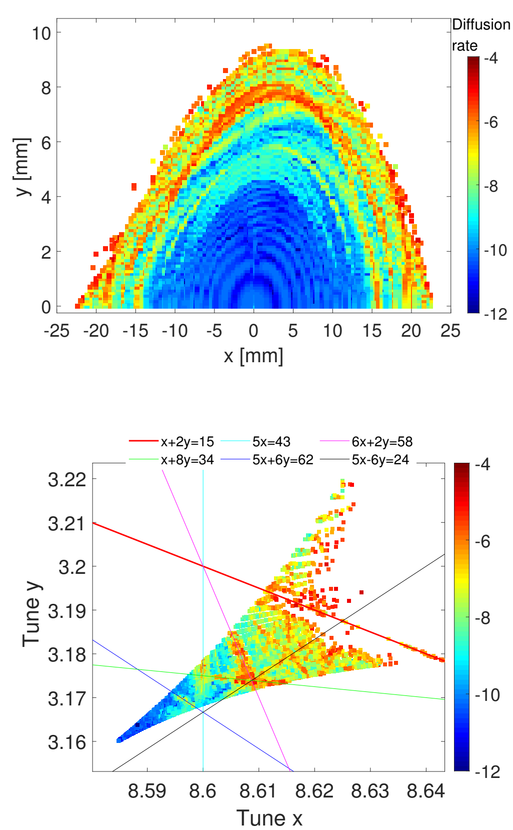

Figure 4: FMA of the optimized DA, tracked at the center of the long straight section. Upper: x-y space. Lower: tune space.

With the same RF cavity of the present HLS storage ring, the momentum aperture of DDBA-H6BA lattice is tracked,

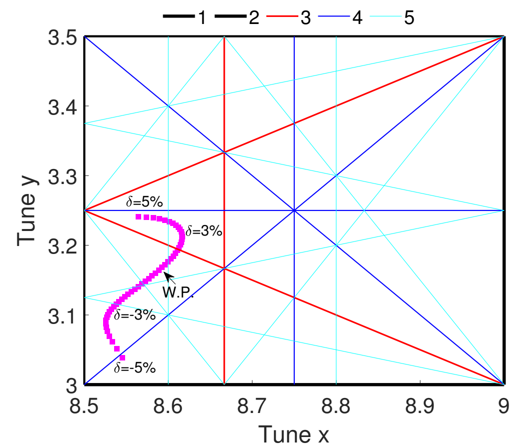

Figure 5: Tune footprints for -5%~5% momentum deviation.

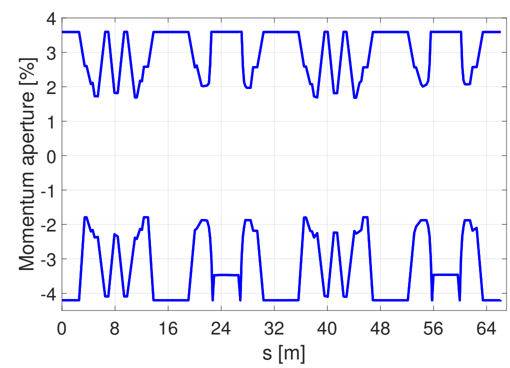

Figure 6: Momentum aperture along the storage ring.

as shown in Fig. 6. The MA at straight sections are about 3%~4% and larger than 1.5% at the dispersion bump. With the same condition in the IBS effect calculation, the Touschek lifetimes of this new storage ring are about 3.3 h and 4.1 h for 5% and 10% transverse coupling, respectively.

CONCLUSION

In this paper, we proposed a DDBA-H6BA lattice and applied it to the design of the potential upgrade of HLS storage ring. Compared to the present HLS storage ring designed with DBA lattice, the natural emittance is significantly reduced from 36.4 nm·rad to 1.8 nm·rad at the cost of two short straight sections. Due to the low emittance and beta functions, the synchrotron radiation brightness can be enhanced by more than one order of magnitude. Benefiting from the optimization of nonlinear dynamics indicators and the $-I$ transformation approximatively achieved between sextupoles, the DA and MA are large enough which promise a reasonable injection efficiency and lifetime.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (No. 12205299, 11875259) and the Fundamental Research Funds for the Central Universities (No. WK2310000107).

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