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# A TEN-BEND ACHROMAT LATTICE WITH INTERLEAVED DISPERSION BUMPS FOR A DIFFRACTION-LIMITED STORAGE RING

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*Abstract*

Recently, a multi-bend achromat (MBA) lattice concept, called the MBA with interleaved dispersion bumps (IDB-MBA), was proposed to design the HALS storage ring, which presented better performance of both on- and off-momentum nonlinear dynamics. Since the beam emittance scales inversely with the third power of the number of bending magnets, in this paper we will study a new IDB-MBA lattice with more bending magnets. It is feasible to satisfy the requirement of the IDB-MBA concept in a 10BA lattice, and an IDB-10BA lattice is then designed for a storage ring light source with an energy of 2.4 GeV. The designed lattice has an ultra-low natural emittance of 81 pm·rad, and a dynamic aperture of about 6 mm and a large dynamic momentum aperture of 6% are achieved.

## INTRODUCTION

For a storage ring light source, since the beam emittance is proportional inversely to the third power of the number of bending magnets (bends), a very effective way to reduce the emittance is to employ more bends. So multi-bend achromat (MBA) lattices have been widely adopted to design diffraction-limited storage rings (DLSRs) with emittances of hundreds or even tens of pm·rad. Besides, employing longitudinal gradient bends (LGBs) and reverse bends (RBs) [1] can further reduce the emittance. Lower emittance generally means stronger nonlinear dynamics effects. To improve the performance of nonlinear dynamics, nonlinear cancellation schemes are usually required in the lattice design of DLSRs.

Inspired by the hybrid MBA [2] and locally symmetric MBA [3] lattice concepts, recently we proposed an MBA with a novel nonlinear cancellation scheme for the design of HALS, which was called the MBA with interleaved dispersion bumps (IDB-MBA) [4]. In the IDB-MBA lattice, two pairs of interleaved dispersion bumps are created, and like in the hybrid MBA, the phase advances between each pair of bumps are set to such values as to cancel out the nonlinear effects caused by sextupoles. Due to two dispersion bumps created, the IDB-MBA can have more families of sextupoles than the hybrid MBA, which can be used to better control tune shifts with momentum so as to enlarge dynamic momentum aperture (MA). Several IDB-7BA lattices have been studied for the HALS [5], showing better performance of both on- and off-momentum nonlinear dynamics.

In this paper, we will explore the IDB-MBA lattice concept, and a new IDB-MBA lattice with more bends will be studied. In this study, a DLSR with the same energy as HALS will be designed with the new IDB-MBA lattice towards a natural emittance of less than 100 pm·rad.

## LATTICE DESIGN

In an IDB-MBA lattice, the horizontal and vertical phase advances between two pairs of dispersion bumps, $(\Delta\mu_{x1}, \Delta\mu_{y1})$ and $(\Delta\mu_{x2}, \Delta\mu_{y2})$ roughly satisfy:

$$\Delta\mu_{x1} = (2m_1 + 1)\pi, \Delta\mu_{y1} = n_1\pi, \quad (1)$$

$$\Delta\mu_{x2} = (2m_2 + 1)\pi, \Delta\mu_{y2} = n_2\pi, \quad (2)$$

where $m_1$, $n_1$, $m_2$ and $n_2$ are integers. The conditions of phase advance are to cancel out the nonlinear effects of normal sextupoles. In the IDB-7BA lattice, $(\Delta\mu_{x1}, \Delta\mu_{y1})$ and $(\Delta\mu_{x2}, \Delta\mu_{y2})$ are both $(3\pi, \pi)$ [4], as shown in the upper plot of Fig. 1. To develop a new IDB-MBA lattice with more bends, we can add three more combined function bends into the center of the IDB-7BA lattice, and then an IDB-10BA lattice can be formed with $(\Delta\mu_{x1}, \Delta\mu_{y1})$ equal to $(5\pi, \pi)$, as shown in the lower plot of Fig. 1.

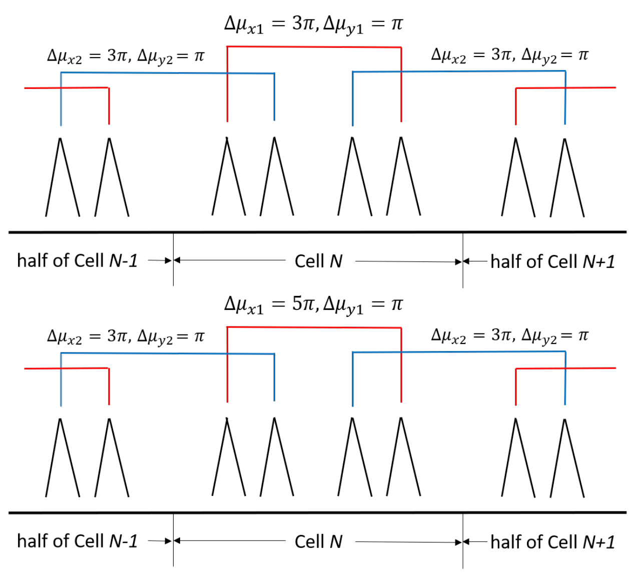


Figure 1: Schematics of the 7BA lattice (upper) and 10BA lattice (lower) with interleaved dispersion bumps.

### *Linear Optics Design*

Now we use the IDB-10BA lattice to design a DLSR with an energy of 2.4 GeV. The ring consists of 14 identical lattice cells with a circumference of 384 m. In the design, the linear optics and parameters were optimized using multi-objective genetic algorithm. To search for better lattice solutions, various magnet parameters were taken in the optimization

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as decision variables, including dipole and quadrupole field strengths of all bends and quadrupole magnets, as well as lengths of bends and drifts. After the optimization, one lattice solution was chosen. The linear optical functions and magnet layout of the lattice are shown in Fig. 2. There are four LGBs at both sides of the arc section, and their dipole field profiles are shown in Fig. 3. Two RBs with horizontally focusing quadrupole field are located in the second and third dispersion bumps. The other bends are combined function ones. With these bends, an ultra-low natural emittance of 81 pm·rad was achieved. The main parameters of the designed storage ring are listed in Table 1. The maximum strength of quadrupoles in the lattice center region with small dispersion is 84 T/m, and the strengths of the other quadrupoles are less than 45 T/m.

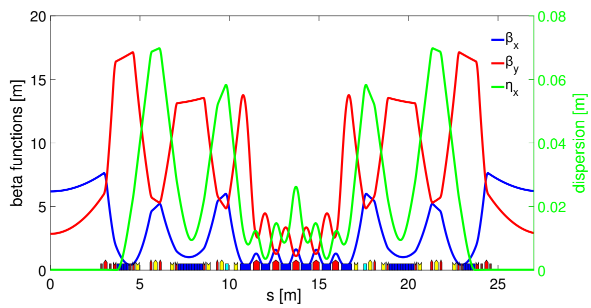


Figure 2: Linear optical functions and magnet layout of the IDB-10BA lattice. In the magnet layout, bends are in blue and cyan (RBs), and quadrupoles, sextupoles and octupoles in red, yellow and brown, respectively.

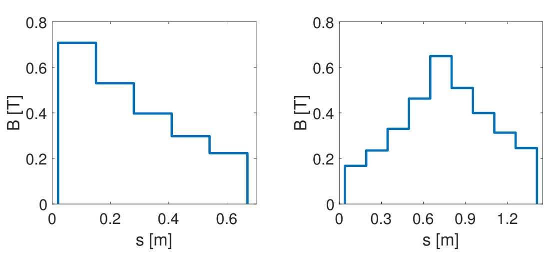


Figure 3: Dipole field profiles of the first (left) and second (right) LGBs. The profiles of the other two LGBs are mirror-symmetrical with these two ones.

## *Nonlinear Dynamics Optimization*

The phase advances between each pair of dispersion bumps, shown in the lower plot of Fig. 1, can provide a very effective cancellation of nonlinear effects for the sextupoles in the bumps. In addition, another nonlinear cancellation was also made over some lattice cells. Inspired by the cancellation scheme of the SLS-2 lattice [6], the horizontal and vertical tunes of one lattice cell of our IDB-10BA were set to near $(3\frac{3}{7}, \frac{6}{7})$ in the lattice design so as to minimize resonance driving terms over 7 identical lattice cells. Due to that there are six families of sextupoles, momentum dependent tune shift terms can generally be well controlled. Besides

Table 1: Main Parameters of the Designed Storage Ring

| **Parameters** | **Values** |
|---|---|
| Beam energy | 2.4 GeV |
| Circumference | 384 m |
| Natural emittance | 81 pm·rad |
| Number of lattice cells | 14 |
| Length of long straight sections | 5.6 m |
| Transverse tunes | 48.20/12.20 |
| Natural chromaticities | -64/-66 |
| Momentum compaction factor | $1.17\times10^{-4}$ |
| Natural rms energy spread | $7.72\times10^{-4}$ |
| Damping partition numbers (H/V/E) | 1.91/1/1.09 |
| Radiation loss per turn (bare lattice) | 227.6 keV |
| $\beta_x$ and $\beta_y$ at long straight sections | 6.19 m/2.86 m |

sextupoles, we also introduced three families of octupoles that were mainly used to control amplitude dependent tune shift terms. The arrangement of these octupoles is shown in Fig. 2, similar to that of the MAX IV light source [7].

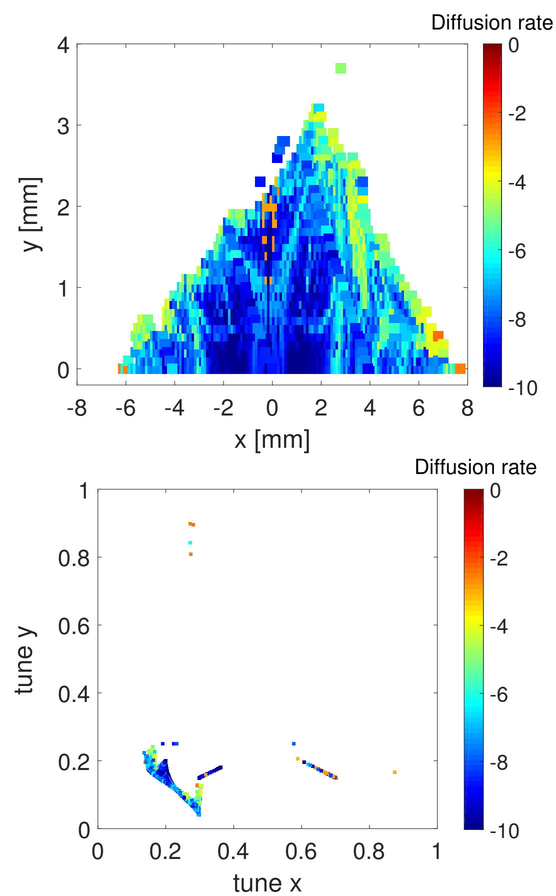


Figure 4: FMA of the optimized DA. Upper: x-y space. Lower: tune space.

Six families of sextupoles and three families of octupoles were employed to optimize the nonlinear dynamics using a multi-objective particle swarm optimization algorithm. In the optimization, the objective functions were the dynamic aperture (DA) and dynamic MA at the middle of long straight sections, and the chromaticities were corrected to (3, 3). Figure 4 show the frequency map analysis (FMA) of the optimized DA, which is tracked for 1024 turns with the Elegant code. It can be seen that the horizontal DA is larger than 6 mm and the vertical is about 2 mm. The tune shifts with momentum are shown in Fig. 5, and we can see that the dynamic MA at the long straight section is 6%. The horizontal DAs for particles with momentum deviations from -5% to 5% are shown in Fig. 6, and we can see that off-momentum DAs do not shrink too much compared to the on-momentum DA.

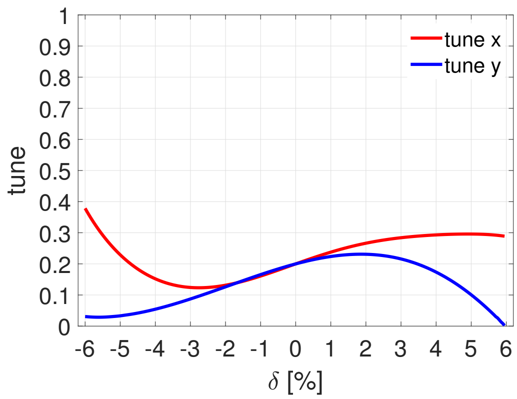


Figure 5: Transverse tunes v.s. momentum deviations.

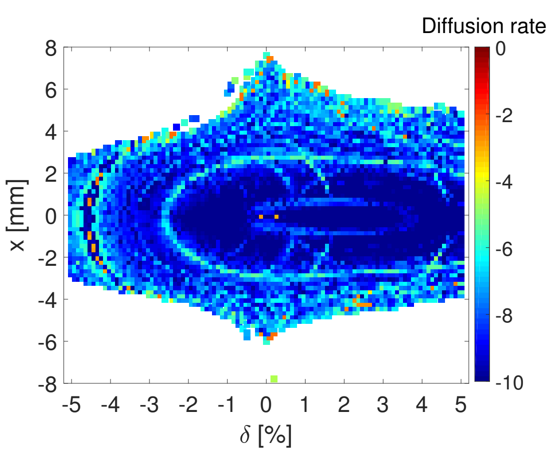


Figure 6: Horizontal DAs v.s. momentum deviations.

With longitudinal motion and errors included, the on-momentum DA will be reduced, and it is impossible to implement an off-axis injection. However, due to large dynamic MA and acceptable off-momentum DAs, on-axis longitudinal injection scheme [8] can be considered, which alleviates the requirement for a large on-momentum DA. In this lattice, full-coupling beam can be produced by using the linear coupling resonance, which will benefit emittance reduction and mitigate scattering-induced effects.

## CONCLUSION

In this paper, we proposed an IDB-10BA lattice by adding three more bends into the center part of the IDB-7BA lattice proposed for designing the HALS storage ring. A 2.4 GeV light source with a natural emittance of 81 pm·rad was designed based on this 10BA lattice with LGBs and RBs employed. Benefiting from the nonlinear cancellation within each pair of dispersion bumps, most of nonlinear effects could be minimized within one lattice cell. An additional nonlinear cancellation was also done over seven lattice cells. Besides, momentum and amplitude dependent tune shifts could be controlled by the sextupoles located in the dispersion bumps and three families of octupoles. With these strategies, a horizontal DA of larger than 6 mm and a dynamic MA of 6% were achieved, as well as acceptable off-momentum DAs, which could allow a longitudinal injection scheme.

## ACKNOWLEDGEMENTS

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