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PRELIMINARY STUDY OF A NINE-BEND ACHROMAT LATTICE FOR A DIFFRACTION-LIMITED STORAGE RING

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Abstract

In recent years, multi-bend achromat (MBA) lattices have been widely used for the design of diffraction-limited storage rings (DLSRs) being developed around the world as the next-generation storage ring synchrotron sources. To better solve the problem of very serious nonlinear dynamics in the DLSR lattice design, recently we proposed a new MBA lattice concept called the MBA lattice with interleaved dispersion bumps [1], which was then applied to designing 7BA lattices for the Hefei Advanced Light Source (HALS), with the result showing rather good nonlinear dynamics performance. In this paper, a 9BA lattice also following our MBA concept is preliminarily designed as a possible option for the HALS with a natural emittance of less than 30 pm·rad. Since generally the 9BA lattice can have a much lower emittance than the usually used 7BA lattice, the work in the paper will provide an inspiration for the existing third-generation synchrotron sources to upgrade to DLSRs with much lower emittances.

INTRODUCTION

Synchrotron radiation has been widely used in material science, crystallography, photetch, bio-medicine and so on. The user community has an intensely demand for high brightness and good coherence. The primary way to enhance the brightness and coherence of synchrotron radiation produced by an electron storage ring is to reduce the electron beam emittance. If the emittance is sufficiently small, reaching the diffraction limitation of the synchrotron radiation, the storage ring is called a diffraction limited storage ring (DLSR). The diffraction limited emittance is given by $\varepsilon \leq \lambda/4\pi$ for Gaussian beam [2], where λ is the wavelength of the photon beam. For the soft X-ray with a wavelength of 1 nm, the diffraction limited emittance should be less than 80 pm·rad.

Since emittance is proportional inversely to the third power of the number of dipoles, the most effective way to reduce emittance is to apply the multi-bend achromat (MBA) lattices. The structure of the MBA lattice consists of several middle units and a matching section at each side followed by a long straight section. Benefit from the increased number of bending magnets, the emittance can be dramatically reduced to sub-nm·rad or even tens of pm·rad. The MAX-IV and Sirius storage rings which exploit MBA lattices have been constructed, whose natural emittances are about 330 pm·rad and 250 pm·rad, respectively [3-4]. ESRF, APS, SOLEIL and some others are planning on or in process of upgrading their light sources applying with MBA lattices. Our NSRL also proposed a soft X-ray DLSR called Hefei Advanced Light Source (HALS) since HLS-II cannot meet users' demand gradually [5, 6]. The emittance of HALS aims to be less than 50 pm·rad.

Such a low emittance normally generates very serious nonlinear dynamics. To better solve this problem, ESRF proposed a concept called hybrid MBA, in which a pair of dispersion bumps can assist in reducing the required chromatic sextupole strengths while efficiently cancelling out many nonlinear effects within one cell [7]. However, the limited number of adjustable knobs (i.e. the number of sextupoles) is not enough to obtain both a large dynamic aperture (DA) and a sufficient momentum aperture (MA) if the emittances are much lower like that of APS-U, HEPS, etc. To further improve the nonlinear dynamics performance of the hybrid MBA lattice, we proposed two concepts called locally symmetric MBA lattice [8] and MBA lattice with interleaved dispersion bumps recently [1]. We have applied these two concepts to designing MBA lattices for the HALS with very low emittances and good nonlinear dynamics performances. In this paper, we will present a preliminary result of a 9BA lattice applied with the latter concept with a natural emittance less than 30 pm·rad, and simultaneously, a fairly good nonlinear dynamics performance. This lattice will be a possible option for the HALS.

THE 9BA LATTICE

The concept of the MBA lattice with interleaved dispersion bumps can be described with the help of Fig. 1. Consider of three adjacent cells C1, C2 and C3. In cell C2, the first and the fourth dispersion bumps, denoted as $B_{2,1}$ and $B_{2,4}$, form one pair of dispersion bumps. While the $B_{2,2}$ and the $B_{1,3}$ which is in the former cell form another pair of dispersion bumps. The phase advances for the non-linear cancellation between each pair of two bumps are

$$\mu_x = (2m+1)\pi, \mu_y = n\pi \tag{1}$$

for normal sextupoles, where m and n are integers. If n is an odd number, the transformation between each pair of two bumps will be $-I$ transformation. From the nonlinear cancellation point of view, the pairs of bumps are interleaved.

Following this concept, we designed a 9BA lattice. The magnet layout and linear optical functions are shown in Fig. 2, and some main parameters of the 9BA lattice are listed in Table 1. To further reduce the emittance, all bending magnets are combined function ones, with the field strength of 0.35 T and the transverse gradient of less than 31 T/m. The maximum gradients of quadruples in this 9BA lattice reach up to 108 T/m, which is almost the state-of-the-art. The length of per cell of the lattice is 24 m. To re-

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serve adequate space at bumps, where β-functions and dispersion can grow, the arrangement of middle part of the lattice is very compact. This is the very reason why we need such high gradient magnets.

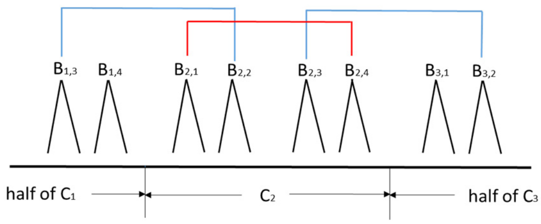

Figure 1: Schematic of the MBA lattice with interleaved dispersion bumps. The nonlinear cancellation is made between each pair of dispersion bumps.

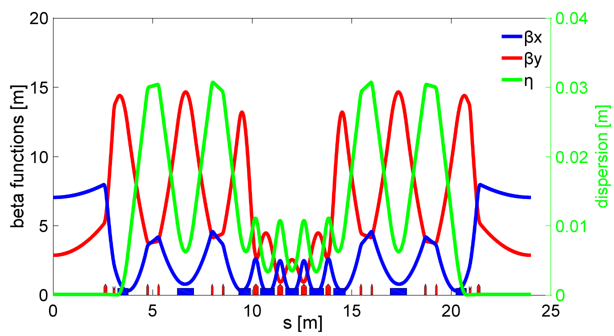

Figure 2: Linear magnet layout and linear optical functions of the HALS 9BA lattice.

Table 1: Main Parameters of the HALS 9BA Lattice Ring

Parameter	Value
Beam energy	2.4 GeV
Circumstance	576 m
Number of cells	24
Natural emittance	25.6 pm·rad
Damping partition numbers(x/y/z)	1.57/1/1.43
Transverse tunes	81.34/20.38
Natural chromaticities	-126/-108
Momentum compaction factor	6.06×10^{-5}
Length of long straights	5.1 m
Natural energy spread	5.08×10^{-4}
Radiation loss per turn (bare lattice)	0.128 MeV

From Figure 2, we can see that four dispersion bumps are created between dipoles 1-2, 2-3, 7-8 and 8-9. The 1st and 4th dispersion bumps form the first pair, and the 2nd bump of the present cell and the 3rd bump of the previous cell form the second pair of bumps. At the beginning of our optimization process, we chose (82.3, 49.2) as the transverse tunes. And set the phase advances between each pair of dispersion bumps at 5π and 3π in the horizontal and vertical directions, respectively. But the results show that the MA is only 1%, which means that this pair of tunes doesn't suit our 9BA lattice. So we change the tunes to (81.3, 20.3). The phase advance between the 1st bump and the 4th bump is 5π and π in the horizontal and vertical directions, respectively. While the phase advance between the 2st bump of the present cell and the 3rd bump of the previous cell is 3π and π in the horizontal and vertical directions, respectively. After optimization, the preliminary result is not bad.

We applied NSGA-II (Non-dominated Sorting Genetic Algorithm II) to optimize the linear optical functions. The optimized variables include the lengths and strengths of magnets, the lengths of the place where bumps are located and the lengths of some drifts. The objective functions are the emittance and the dispersion functions at the middle of the long straights. Some constraints are necessary so as to satisfy our new MBA concept and improve the performance of this lattice, listed as follows,

- The dispersion values at bumps should be large enough so as to decrease the sextupole strength.
- The phase advances between dispersion bumps should roughly satisfy $-I$ transformation.
- The transverse tunes of a cell should be close to the set value.
- The beta functions between the fourth bend and the sixth bend are limited at relatively low values.

These constraints in linear optimization will benefit to the nonlinear optimization.

NONLINEAR OPTIMIZATION

Six families of sextupoles (three families for each pair of bumps) were employed for chromaticity correction and nonlinear dynamics optimization. Except the two families of sextupoles for chromaticities correction, there are four free families of sextupoles for nonlinear optimization. With the help of these four knobs, many nonlinear terms can be adjusted relatively easier.

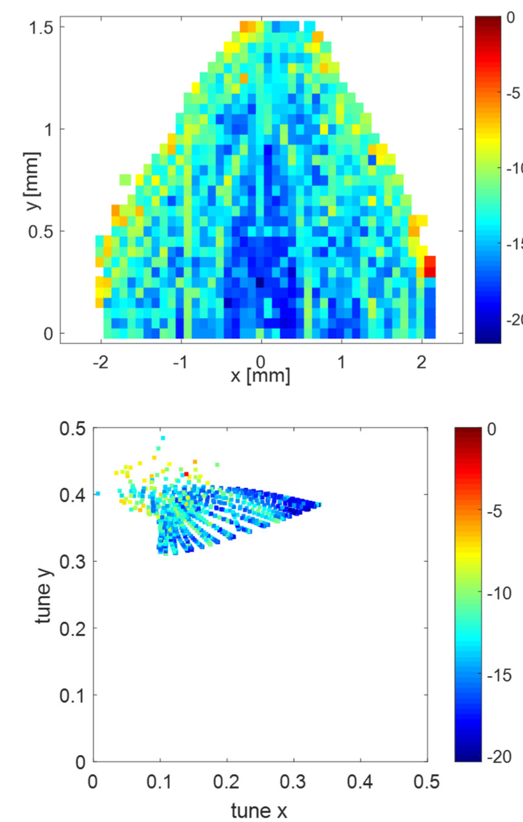

Figure 3: Frequency map analysis for the DA.

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MOPSO was applied in the nonlinear optimization. Figure 3 and Fig. 4 show the frequency map analysis (FMA) for the DA and off-momentum DAs of this 9BA lattice, respectively. The result shows the on-momentum DA are about 2 mm and 1.5 mm in the horizontal and vertical directions, respectively. And the off-momentum DAs are also relatively large. The tune shift with momentum is shown in Fig. 5, with a local MA at long straight sections larger than 3.5% without crossing half-integer resonance lines. The preliminary optimization results of MA is not as large as that in the 7BA lattice. Nevertheless, this result is acceptable and can be further improved in the next optimization works. The strength of the sextupole adjacent to the third bending magnet is much small than others according to the optimization results. Such case essentially means that this knob is not sufficiently utilized. So in the next work, we will keep on adjusting linear optical functions to make use of this knob. Besides, the prospective result can be further improved by organizing sextupoles into more families and exploiting octuples.

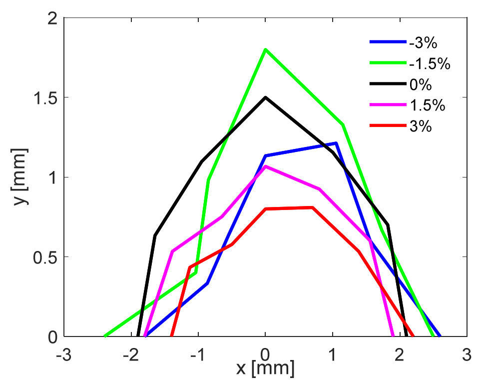

Figure 4: The off-momentum Das.

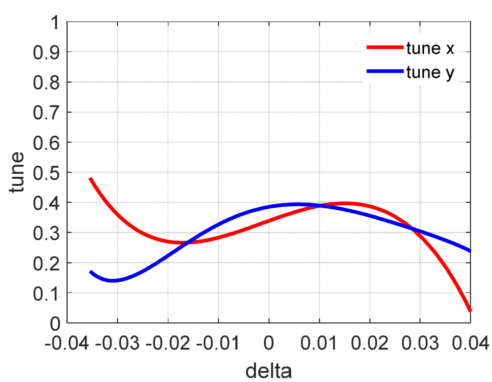

Figure 5: Tunes versus momentum deviation.

CONCLUSION

Following the concept of the MBA lattice with interleaved dispersion bumps, we designed a 9BA lattice with a natural emittance of 25.6 pm·rad within 576 m as a possible option for HALS. This emittance can reach the diffraction limitation of photons with 0.3 nm about 4 keV. Storage rings with such low emittances can be called real sense of DLSRs, compared to MAX-IV and Sirius.

In spite of such a low emittance, reasonable DA and MA are achieved. The preliminary optimization result is not as good as that of the 7BA lattice we have designed, but is acceptable. We will further optimize the linear optical functions and carry out the nonlinear optimization with more families of sextupoles and octupoles which can control high order chromaticities. This design process of 9BA lattice may provide an inspiration for the upgrade of the existing third-generation synchrotron sources.

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