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DESIGN OF A HYBRID SEVEN-BEND-ACHROMAT LATTICE FOR A HIGH-ENERGY DIFFRACTION-LIMITED STORAGE RING USING A NEW OPTIMIZATION METHOD

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Abstract

Recently, we proposed a new optimization method, with nonlinear dynamics indicators considered in the linear optics design, for designing hybrid multi-bend-achromat (MBA) lattices. With this method, two hybrid MBA lattices for medium-low-energy diffraction limited storage rings (DLSRs) have been designed, showing remarkable effectiveness in improving nonlinear dynamic performance. In this paper, we will apply this optimization method to the design of a hybrid 7BA lattice for a 6 GeV DLSR with the same circumference as that of HEPS. In the design, the strengths and arrangement of magnets of this lattice also meet the engineering requirement for HEPS. The designed lattice has a natural emittance of 34 pm·rad. The nonlinear dynamic performance is satisfactory, with a dynamic aperture of about 6 mm and 3 mm in the horizontal and vertical directions, respectively, and a dynamic momentum aperture of larger than 5%, which also shows the power of our optimization method.

INTRODUCTION

The diversity of linear optics solutions is of significant importance to the nonlinear dynamics performance for the hybrid multi-bend-achromat (MBA) type lattices [1, 2]. To further explore the nonlinear dynamics performance of this kind of lattice, recently, we proposed a new optimization method for designing hybrid MBA lattices, where two nonlinear dynamics indicators were taken into consideration during the linear optics design. One is the natural chromaticity, an approximate symbol of the severity of nonlinear dynamics. The other is the sextupole strength, which is generally expected to be weaker. By employing these two indicators as objective functions in designing the linear optics using evolutionary algorithms, the solutions selected from the balance of natural chromaticity and sextupole strength generally have favorable nonlinear dynamics.

With this optimization method, we have designed a hybrid 7BA lattice and a hybrid 10BA lattice for 2.4 GeV diffraction-limited storage rings (DLSRs) with circumferences of 576 m and 324 m, respectively. The former [1] has an ultra-low natural emittance of about 60 pm·rad, with a large dynamic aperture (DA) of about 15 mm and a dynamic momentum aperture (MA) of 4.3%. The latter also has a rather good nonlinear dynamics performance with an emittance lower than 130 pm·rad. In this paper, we will apply this optimization method to design a hybrid 7BA lattice with a natural emittance of tens of picometers for a high-energy DLSR, which has the same energy and circumference as those of HEPS [3]. The strengths and arrangement of magnets of this lattice will also satisfy the requirement of HEPS. Note that the HEPS consists of 24 super-periods, while the DLSR designed in this paper has 48 identical cells.

LATTICE DESIGN

The optimization method will be first described, and then applied to the design of a hybrid 7BA lattice for a high-energy DLSR.

The Optimization Method with Nonlinear Dynamics Indicators Considered

In the optimization method, besides the natural emittance ϵ_{nat} or brightness, two nonlinear dynamics indicators are also choosen as objective functions. The first one is the sum of the absolute values of natural chromaticities, $|\xi_{sum}| = |\xi_x| + |\xi_y|$, and the second one is the sum of the integral strengths of three families of sextupoles, $|I_{sum}| = |I_{SD1}| + |I_{SF}| + |I_{SD2}|$. To calculate $|I_{sum}|$, the focusing sextupole SF is first treated as a sum of SFa and SFb. Then three families of sextupoles are divided into two pairs, (SD1, SFa) and (SD2, SFb), to contribute 2/3 and 1/3 of the chromaticity correction, respectively. A larger contribution from (SD1, SFa) provides a better nonlinear dynamics performance.

With the same circumference (1360.4 m), length of long straight sections (6.086 m) and engineering requirements, including adequate spaces between magnets and feasible magnet strengths, as those of HEPS, we will design a hybrid 7BA lattice for a 6 GeV DLSR. In the linear optics design, various magnet parameters were included as decision variables for better optimization. Reasonable solutions require two constraints:

- transverse tunes: (114.2, 43.2) ± 0.25, and
- horizontal and vertical phase advances between the pair of dispersion bumps $(\Delta\mu_x, \Delta\mu_y)/2\pi$: (1.5, 0.5) ± 0.02.

In the preliminary design for this lattice, we employed only one nonlinear dynamics indicators, $|I_{sum}|$, as an objective function for a faster and better convergence, since $|I_{sum}|$ is quite a good nonlinear dynamics indicator as demonstrated in Ref. [1]. We found that the natural chromaticities had roughly positive relevance with the beta functions in the dispersion bumps (β_{bump}), so we set the third constraints: $\beta_{bump} < 25$ m.

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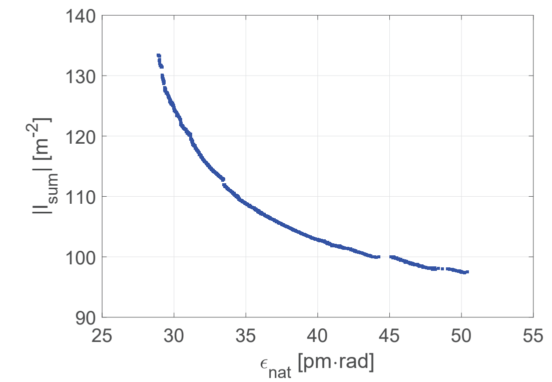

Figure 1: Distribution of the objective function values of solutions of the last generation.

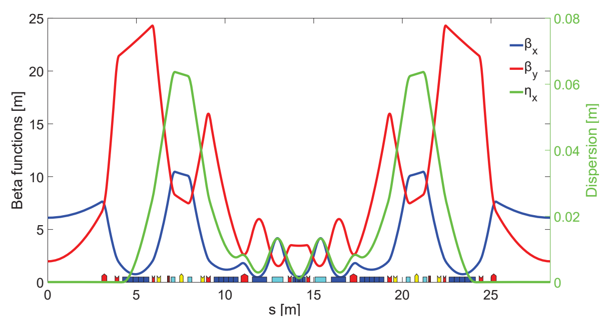

Figure 2: Linear optical functions and magnet layout of the selected lattice. In the magnet layout, bends are in blue and cyan (RBs), quadrupoles in red, sextupoles in yellow and octupoles in brown.

Linear Optics Design

W use this optimization method for the linear optics design of a hybrid 7BA lattice. With the settings mentioned above, multi-objective genetic algorithm was carried out with a population of 10,000 for 600 generations. Figure 1 shows the objective function values of the solutions from the last generation and we can see that ϵ_{nat} varies from 29 pm·rad to 51 pm·rad. Then, several solutions with ϵ_{nat} lower than 40 pm·rad which have different $|I_{sum}|$ were selected for further nonlinear optimization. Figure 2 shows the linear optical functions and magnet layout of one selected lattice with ϵ_{nat} of 34 pm·rad which has a better nonlinear dynamic performance.There are five longitudinal gradient bends (LGBs) in the lattice, with dipole field profiles shown in Fig. 3. The maximum dipole field of the third LGB, located in the middle of the lattice, is 1 T, from which a beam line for hard X-ray can be extracted. Reverse bends (RBs) with horizontally focusing quadrupole fields were also employed to further reduce emittance, with the arrangement similar to that of the APS-U lattice [4]. The strengths of the RBs located in the dispersion bumps are less than 50 T/m and the strengths of the other RBs are less than 65 T/m. The maximum strength of the quadrupoles in the low-dispersion region is about 80 T/m and the strengths of other quadrupoles are less than 58 T/m. Table 1 lists the main parameters of the storage ring with this lattice.

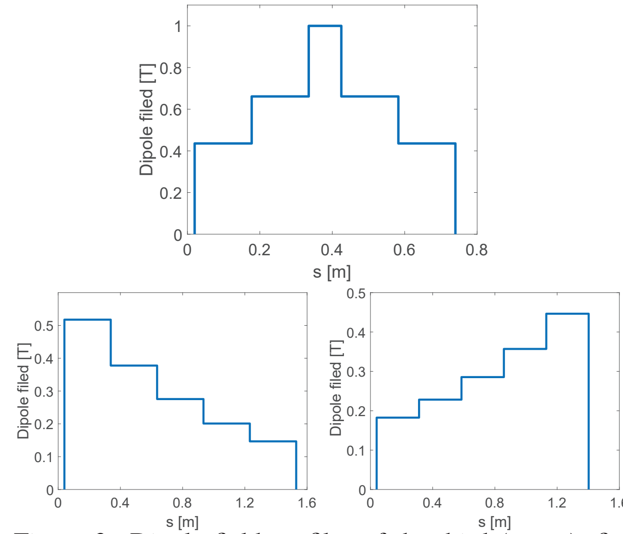

Figure 3: Dipole field profiles of the third (upper), first (left lower) and second (right lower) LGBs. The profiles of the fourth and fifth LGBs are mirror-symmetrical with the second and first ones.

Nonlinear Dynamics Optimization

The DA and MA of this lattice were further optimized using a multi-objective particle swarm optimization algorithm with three families of sextupoles and one family of octupoles employed. Note that they were not organized into more families like APS-U and HEPS. During the nonlinear optimization, we found that it was better for both DA and MA if the octupoles were located between SD1 and SF. With chromaticities corrected to (5, 4), the frequency map analysis (FMA) of the optimized DA, tracked at the middle of long straight sections for 1024 turns using the *Elegant* code, is shown in Fig. 4. The horizontal DA is about 6 mm and the vertical DA is about 3 mm. Fig. 5 shows the momentum dependent tune footprints, with the vertical tune crossing the half-integer resonance line at a momentum deviation of 3%. In a 6D tracking, the half-integer line can be crossed. Fig. 6 shows off-momentum DAs, which are also good.

Table 1: Main Parameters of the Designed Storage Ring

Parameters	**Values**
Beam energy	6 GeV
Circumference	1360.4 m
Natural emittance	34.0 pm·rad
Number of lattice cells	48
Length of long straight sections	6.086 m
Transverse tunes	114.10/43.20
Natural chromaticities	-159/-151
Momentum compaction factor	1.5×10^{-5}
Natural rms energy spread	1.0×10^{-3}
Damping partition numbers (H/V/E)	1.86/1/1.14
Radiation loss per turn (bare lattice)	2.78 MeV
β_x and β_y at long straight sections	6.11 m/1.98 m

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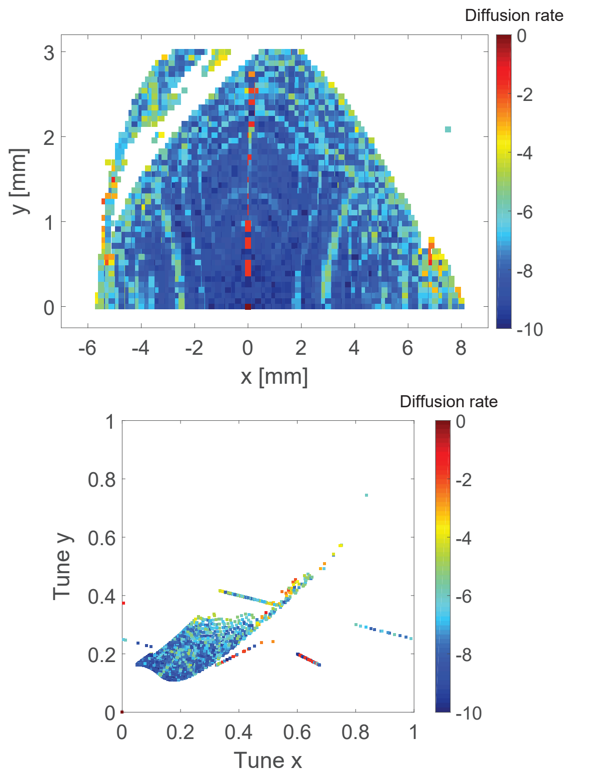

Figure 4: FMA of the optimized DA, tracked at the middle of long straight sections with β_x of 6.11 m and β_y of 1.98 m. Upper: x-y space. Lower: tune space.

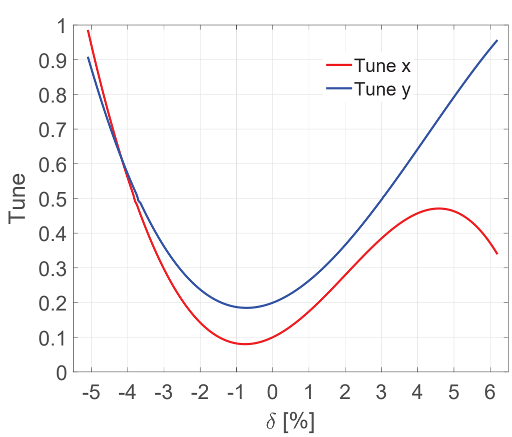

Figure 5: Momentum dependent tune footprints.

We also tracked the DA with longitudinal motion considered, and the horizontal DA was larger than 4 mm and the vertical larger than 2 mm, as shown in Fig. 7. In the tracking, the frequency and voltage of RF cavity are 166.6 MHz and 3.5 MV, respectively. The local MA was also tracked with the same RF cavity, and the result showed that the dynamic MA at long straight sections was larger than 6%, giving an enough Touschek lifetime.

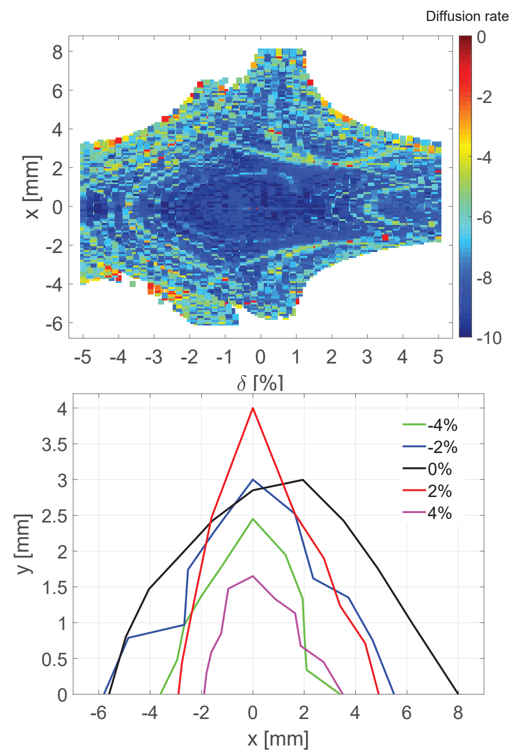

Figure 6: Horizontal DAs for different momentum deviations (upper) and off-momentum DAs (lower).

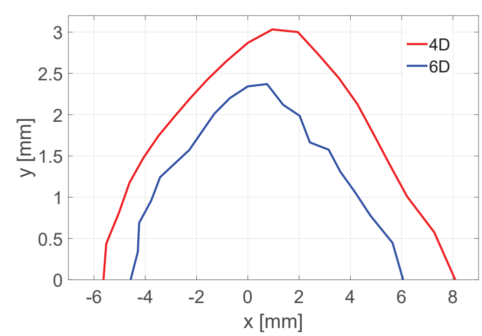

Figure 7: The 4D- and 6D-tracking DAs.

CONCLUSION

Using the optimization method with nonlinear dynamics indicators considered in the linear optics design, we designed a hybrid 7BA lattice with a natural emittance of 34 pm·rad for a DLSR with the same energy and circumference as HEPS. Satisfactory nonlinear dynamics performance was obtained using this optimization method. The DA was about 6 mm and 3 mm in the horizontal and vertical planes, respectively. The off-momentum DAs and 6D-tracking DA are also favorable. The dynamic MA was 3% without crossing the half-integer resonance line and it was larger than 6% in the 6D tracking, which promised a reasonable Touschek lifetime. In the future, we will employ the photon spectral brightness and two nonlinear dynamics indicators as objective functions to further optimize this hybrid 7BA lattice. The working point will also be further studied to search for better solutions.

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