CANDIDATE LATTICE DESIGN OF THE HEPS BOOSTER CONSISTING OF COMBINED-FUNCTION DIPOLES*

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Abstract

The High Energy Photon Source (HEPS) is a 6-GeV, ultralow-emittance, kilometer-scale storage ring light source to be built in China. It is planned to use a 300 MeV linac and a full energy booster as the injector. In this paper we present one of the candidate lattice designs for the HEPS booster, where most of the dipoles are combined with quadrupole and sextupole gradients. Global optimization of the lattice has been done, where the dependencies of the lattice performance on various parameters, including the minimum pole face field, damping partition number, number of dipoles, etc. are discussed.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, ultralow-emittance storage ring light source to be built in the suburb of Beijing, China. The R&D project, HEPS test facility (HEPS-TF) started in 2016. A 7BA ring lattice was developed [1] based on the 'hybrid MBA' concept [2] and used as the baseline lattice of the HEPS-TF, with a circumference of about 1296 m and a natural emittance of about 60 pm at 6 GeV. Since the lattice for the HEPS is under design and optimization and not finally determined yet, other related physics studies for the HEPS, including the booster design, are based on this 60-pm design.

For the booster, there are two options. One is to locate the booster in the same tunnel with the storage ring, while the other is to design a booster with circumference of 1/3 of the storage ring and place it in a separate tunnel. For the latter option, we have designed a 15BA lattice, with a natural emittance of ~4.5 nm at 6 GeV [3]. In this lattice, we combine only the horizontally defocusing gradients into the dipoles, while using separate-function horizontally focusing quadrpoles and sextupoles. A question related to the budget arises then whether we can combine more gradients into the dipoles, similar to the NSLS-II booster [4], so as to greatly reduce the number of the magnets and hence the cost.

To this end, we did detailed design and optimization studies on this type of lattice. Although at the end of 2016, it was decided to not use this type of lattice, it is meaningful to show the underlying considerations for designing such a lattice, which may provide useful reference for other similar lattice designs.

LINEAR OPTICS RELATED ISSUES

Similar to the 15BA lattice designed for the HEPS booster, this lattice is assumed to have 4 super-periods, providing 4 long straight sections to accommodate injection, extraction, and RF systems. The main property of this type of lattice is that most of the quadrupole and sextupole gradients are combined into the dipoles. This, however, will introduce several constraints on the available minimum emittance. First, in this case each unit cell is consisted of two dipoles combined with focusing and defocusing gradients, respectively. This leads to a backward that one cannot simultaneously reduce the optical functions in the two dipoles to be close to the so-called 'theoretical minimum emittance' conditions [5]. Secondly, to reach a low emittance it calls for a large number of dipoles (and hence small bending angles) and strong focusing, which however, for a fixed circumference, implies short dipoles combined with strong focusing gradients and also strong sextupole gradients (to correct the natural chromaticity). This will make the pole face filed of the dipole quickly approaching its upper or lower limit.

Preliminary studies show that it is easier to reach the lower limit (than to reach the upper limit) of the pole face filed, when reducing the emittance. So, we investigate the relationship between the available minimum emittance and the lower limit of the dipole pole face field, for a specific number of dipoles.

For the unit cell, we derive the expressions of the emittance and the pole face field in terms of dipole parameters (not taking into account the sextupole gradients of dipoles). In this way, for an arbitrary set of dipole parameters, we can quickly calculate the corresponding emittance and pole face filed, and do not need to put these parameters in a real lattice model.

This is verified with a comparison study, where two PSO (particle swarm optimization) evolutions are performed over 1000 generations based on the analytical expressions and real lattice models respectively, for the case with 41 dipoles in each super-period. The final solutions of two PSO evolutions are shown in Fig. 1. It appears that these two approaches generate basically the same results. Furthermore, it is much faster for the PSO based on the analytical expressions to reach the so-called Pareto front.

From the PSO optimizations based on analytical expressions, we obtain the dependence curves of minimum emittance versus the minimum pole face field of the dipole, as shown in Fig. 2. For different dipole numbers (namely, different number of unit cells in one super-period), the available maximum cell length is considered to be 84 m/No. of unit cells. And, constraints on tunes, beta functions, etc., were imposed in the optimization, to ensure that the found solutions have satisfying optical parameters.

One can see clearly from Fig. 2 that it does not definitely result in lower emittance with larger number of dipoles.

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Finally, we choose the number of dipoles in one super-period to be 45. In the case with larger number of dipoles, there is just a limited room for further-reduction of the emittance, but with a price of higher cost (more dipoles). In addition, we somewhat arbitrarily set the lower limit of the dipole pole face field to 0.2 T at 6 GeV (corresponding to 100 Gauss at the injection energy 300 MeV). From Fig. 2, such a minimum pole face field corresponds to a minimum emittance of ~5 nm.

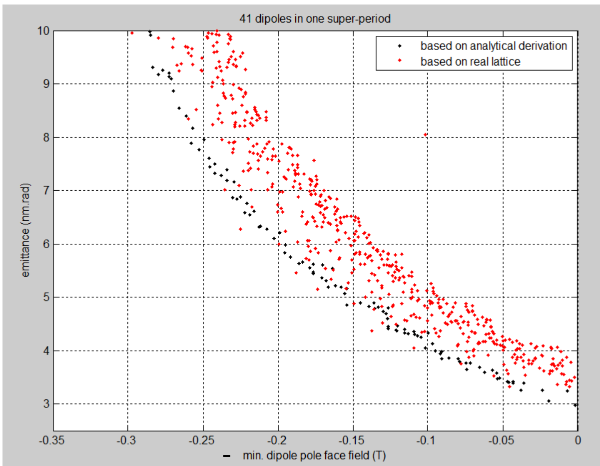

Figure 1: Solutions of PSO evolutions based on anlyatical expression and actual lattice model.

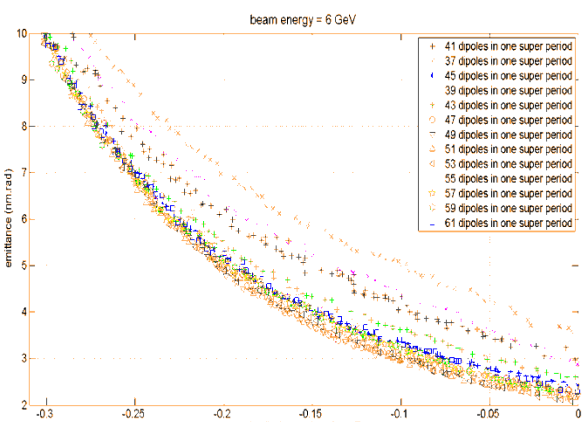

Figure 2: Variation of the available emittance with respect to the minimum dipole pole face filed, for different numbers of dipoles in one super-period, obtained from PSO optimizations based on analytical expressions.

NONLINEAR OPTIMIZATION RELATED ISSUES

From the above estimations, we fix the dipole numbers of each super-period to 45. Then, we perform nonlinear optimizations with the actual lattice model, where the sextupole gradients of dipoles are calculated for corrected chromaticities of (+1, +1), and the dynamic aperture (DA) at the center of the long straight section is also calculated.

The lattice is optimized by iteratively and successively implementing the MOPSO and multi-objective genetic algorithm (MOGA) [6], with two objectives, i.e., the emittance and DA, until the population reaches a good convergence.

The results (not shown here) suggest that it is possible to reach a natural emittance of 4~5 nm at 6 GeV, and simultaneously achieve a DA comparative to the physical aperture (assumed to be 18 mm in both x and y planes).

Nevertheless, we noticed that although the minimum pole face fields of all the solutions are above 0.2 T (assuming the pole width is 18 mm), the quadrupole and sextupoles gradients used in the lattice are quite large. Table 1 lists the dipole parameters of one typical solution, where the dipole parameters of the NSLS-II booster [4] are also presented.

Table 1: Dipole Parameters used in HEPS and NSLS-II booster lattices

Parameters	HEPS	NSLS-II
B(BD)	0.77 T	1.13 T
G(BD)	-30 T/m	-5.6 T/m
G'(BD)	-170 T/m^2	-43 T/m^2
B(BF)	0.34 T	0.46 T
G(BF)	7.7 T/m	8.2 T/m
G'(BF)	58 T/m^2	36 T/m^2

The equation for the dipole pole face is derived,

$$\begin{aligned} &By + Gxy + \frac{G'}{6}(3x^2y - y^3) \\ &= By_0 - \frac{G'}{6}y_0^3 \end{aligned} \quad (1)$$

where B, G, and G' are the dipole field, and the quadrupole and sextupole gradients combined in the dipole, respectively, and y_0 is the half gap of the dipole along the central beam trajectory (with $x = 0$).

Assuming $y_0 = 14$ mm, the pole face profiles of BD and BF with the HEPS and NSLS-II dipole parameters are shown in Figs. 3 and 4, respectively. In these figures, the magnetic field in the middle plane (at y = 0), $B(y{=}0) = B{+}Gx{-}G'x^2/2$, is also plotted (note that for this curve the y axis should be in unit of T, which however, is not specified in Figs. 3 and 4). Different from the pole face profile curves, this curve crosses the x axis (the field becomes 0) at a specific x. For the BD magnets of the HEPS booster, it seems impossible to use only two poles and probably requires another two poles to realize the expected gradients, which will increase the cost of the magnet fabrications.

To overcome this problem, a constraint is imposed that $B(y{=}0)$ should be larger than 0 within a horizontal distance of 45 mm from the central beam trajectory. In addition, it was found that due to strong quadrupole gradients combined in the dipoles, some solutions with low emittance have minus longitudinal damping partition numbers (J_z), which implies the particle motion is naturally unstable in longitudinal plane, and consequently a longitudinal feedback system is needed. Apparently, these solutions should be avoided, because this is contradictory to the

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original motivation of designing such type of lattice, which is to realize a robust performance in a lowest possible cost. Accordingly, an addition constraint is imposed to require that J_z should be larger than 0.2.

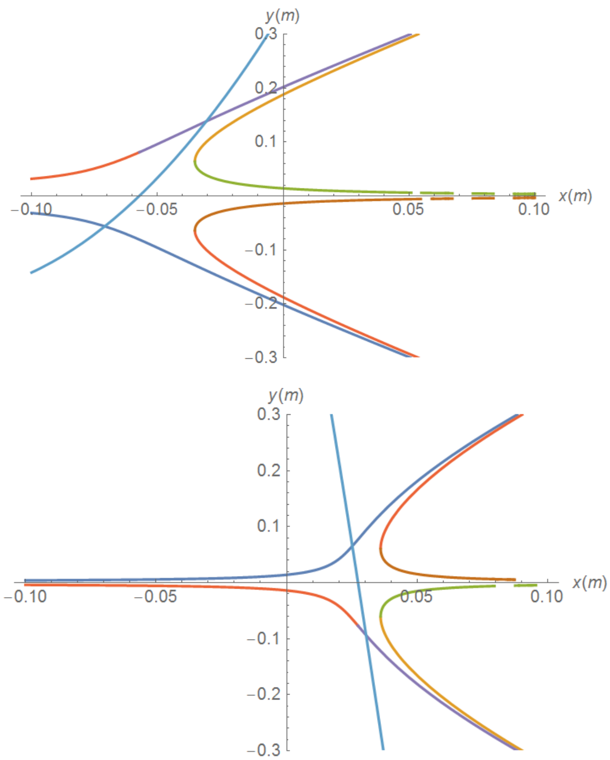

Figure 3: The pole face profiles of BF (upper) and BD (lower) for the HEPS booster, with y_0 = 14 mm.

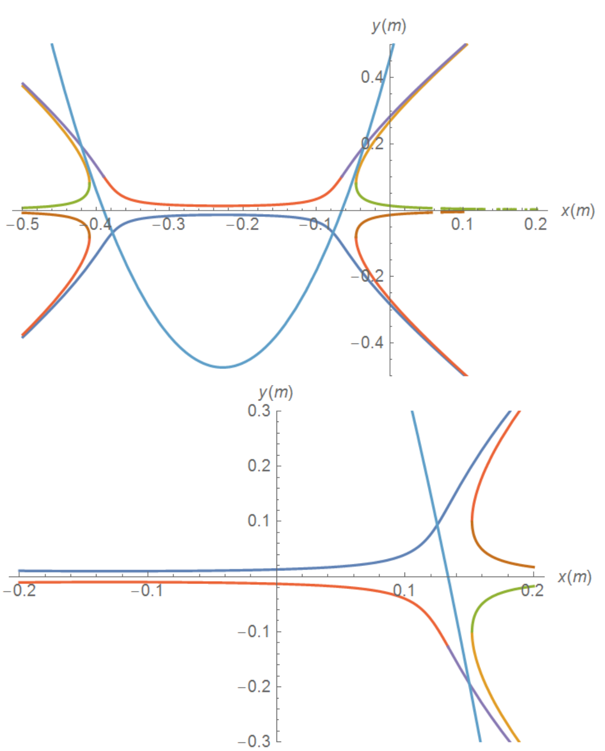

Figure 4: The pole face profiles of BF (upper) and BD (lower) for the NSLS-II booster, with y_0 = 14 mm.

With these two additional constraints, we evolve the population with more generations of PSO and MOGA, with the final solutions shown in Fig. 5. It shows that to reach a large enough DA, the emittance should be about or above 6.4 nm, which is larger than that of the 15BA lattice (4.5 nm). At last, we find a booster lattice, with a natural emittance of 6.7 nm at 6 GeV, J_z = 0.25, and DA similar to the physical aperture (see Fig. 6).

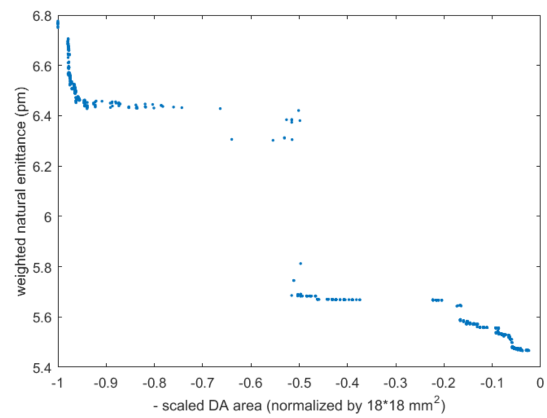

Figure 5: Final solutions after several iterations of PSO and MOGA for the HEPS booster.

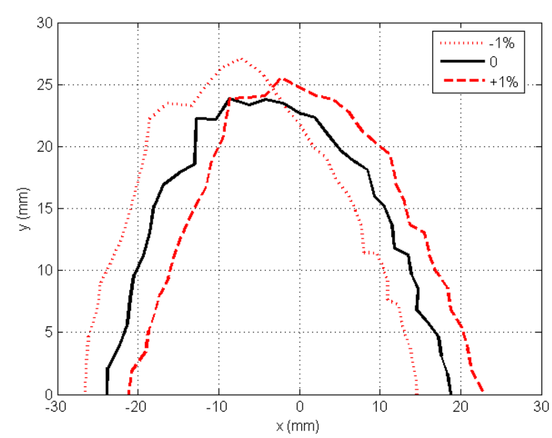

Figure 6: On- and off-momentum DAs for the found lattice for the HEPS booster.

CONCLUSION

In this paper, we present the studies on designing a lattice where most of dipoles are combined with quadrupole and sextupole gradients for the HEPS booster. It turns out that such type of lattice can reduce the number of magnets, but it increases the complexity of magnet fabrication and the difficulty in emittance minimization.

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