DA OPTIMIZATION EXPERIENCES IN THE HEPS LATTICE DESIGN*

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Abstract

In the past decade, the so-called diffraction-limited storage ring (DLSR) light sources were proposed, promising much better radiation performance than available in the existing third generation light sources. Regarding the very strong focusing and chromatic sextupoles that required for reaching an ultralow emittance, to optimize the nonlinear dynamics and achieve an adequate dynamic aperture is an important topic in a DLSR design. In this paper we will present some tips distilled from the DA optimization experience of the High Energy Photon Source over the past ten years, hoping it could provide some aids to other ultralow-emittance designs.

INTRODUCTION

Along with the continuous advance in accelerator technology and unceasing pursuit of higher quality photon flux, the so-called diffraction-limited storage ring (DLSR [1]) light sources, were proposed around the world, to push the brightness and coherence beyond the existing third generation light sources (TGLSs), by reducing the emittance to approach the diffraction-limit for the range of X-ray wavelengths of interest to the scientific community. For example, to reach the diffraction-limit of hard X-ray of 1 Å, we would need to reduce the beam emittances in both horizontal and vertical planes to ~ 8 pm.

To reach a natural emittance as low as possible, multibend achromats (MBAs) lattice consisting of unit cells with compact layout as well as strong focusing (see [2] for a detail discussion) is usually used in a DLSR design. Nevertheless, when the emittance is continuously reduced, nonlinear dynamics gradually becomes a great challenge to the overall ring performance. The strong focusing creates large nonliearities and small dispersions. This, in turn, requires strong sextupoles for chromatic correction. Subsequently, extremely strong nonliearities are introduced, which may cause very small dynamic aperture (DA) and momentum acceptance (MA) and lead to a short beam lifetime and low injection efficiency. Thus, how to control the nonlinearities when minimizing the emittance and obtain adequate DA and MA is an essential issue in a DLSR design (in the following we mainly discuss the DA optimization).

In the past few decades and especially in the past ten years, many advanced analytical and tracking-based nonlinear optimization methods were proposed, for instances, Hamiltonian analysis (e.g., [3]), Lie algebra [4], phase optimization (e.g., [5-6]), multi-objective genetic algorithm (MOGA, e.g., [7-9]), particle swarm optimization (PSO, [10-12]), frequency map analysis [13].

The High Energy Photon Source (HEPS) is an ultralow-emittance, kilometer-scale storage ring light source to be built around Beijing, the north of China. The preliminary lattice design studies of this light source (called Beijing Advanced Photon Source that time) were launched in 2008. In 2016, the R&D project of the HEPS, called the test facility of the HEPS (HEPS-TF) was funded and is to be completed by the end of 2018. The goal of the HEPS-TF project is to develop key hardware techniques that are essentially required for constructing a diffraction-limited storage ring light source, and complete the HEPS design. It is expected to start the HEPS construction soon after the HEPS-TF project is finished.

Up to now, the HEPS lattice has been continuously evolved for about ten years, with emittance reduced by a factor of about 50 (see [14] for details). A hybrid-7BA lattice with antibend and superbend was recently reached for the HEPS, with a natural emittance of 34 pm and adequate ring acceptance for on-axis injection after iterative optimizations [15].

In the following, we would like to present some useful tips distilled from the HEPS DA optimization experience, rather than introducing the detailed and tedious process.

TIPS IN THE DA OPTIMIZATION

Over the past ten years, various linear optics designs were proposed for the HEPS and great efforts were made to explore the best possible nonlinear performance for different lattices, where the nonlinear optimizations were employed. The dependence of the DA on different factors was investigated as a by-product.

Nonlinear Driving Terms vs. DA

Reducing the nonlinear driving terms induced by sextupoles (and octupoles) for improved nonlinear dynamics, is one of the motivations of theoretical analysis of nonlinear dynamics, e.g., Hamiltonian analysis and Lie algebra. This helps to understand the nonlinear behaviour of lattice, e.g., chaotic trajectories and even particle loss. Nevertheless, studies suggest that minimizing the nonlinear driving terms is a necessary but not a sufficient condition of a large DA.

In recent years, the emerged more powerful computing resonances than ever before allows accelerator scientists to evaluate the DA and MA of many different lattices in a reasonable time. This makes it possible to statistical analysis of the correlation between DA and driving terms. The DA studies based on the NSLS-II [8] showed that one design with a large DA always have small driving terms, while small driving terms do not always results in a large DA.

Actually similar phenomenon was observed in our studies. As the first attempt of ultralow emittance design for

the HEPS, a standard 7BA lattice was designed in 2012 [16] with a circumference is 1263.4 m and a natural emittance of 75 pm.rad at 5 GeV. In the nonlinear optimization, to understand the combined effects of multipoles, we developed a theoretical analyser based on Lie Algebra and Hamiltonian dynamics, from which one can obtain analytical expressions of detuning, chromatic, and resonance driving terms with respect to the sextupole and octupole strengths (see Ref. [16] for details). We then made MOGA optimization by setting three objective functions to characterize these nonlinear driving terms. Tracking studies showed that the solutions providing good balance of three objectives did not definitely result in a good nonlinear performance. We needed to verify many candidates with numerical tracking, and chose one solution with the largest DA.

We also tested the feasibility of inserting a few high-beta sections in the lattice to increase the DA (scaling with the square root of beta) and match the optics such that the phase advance of the high-beta section is the same as that of a normal section, or with a difference of $2n\pi$ (n is integer) to restore the periodicity [17]. In this case, it was noticed that the analytical analyser failed to predict correctly the tune shift momentum deviation. The reason is found that the nonlinear driving terms are derived based on the small perturbation assumption that the difference in phase advance basically holds as momentum is deviated, which, however, does not accord with the actual circumstances. Considering the limitation of the theoretical analysis, in the subsequent HEPS design and optimizations, we gave up the optimization of the nonlinear driving terms, and directly use the DA and MA as optimizing objectives.

Phase Optimization vs. DA

In the nonlinear optimizations of the TGLSs, phase optimization has been expected to be able to improve the nonlinear beam dynamics (see, e.g., [18]). Two representative phase optimization approaches proposed in DLSR designs are the so-called 'fourth-order geometric achromat' [5] and '$-I$ transportation between sextupole pairs' [6], or namely, the global and local cancellation schemes. The global cancellation scheme is to construct identity transportation by using several MBAs. It was found in this way most of the third and fourth order resonance driving terms can be cancelled. On the other hand, the local cancellation scheme is to employ a $-I$ transport line (with a phase advance of $2n\pi+\pi$) between two identical sextupoles. In a simple case with thin-lens sextupole model and without other nonlinear elements in between, the nonlinear kicks of sextupoles can be completely cancelled with $-I$ transportation.

It is expected that the lattice designs following these schemes could provide a good start point for further optimization. Nevertheless, studies indicate that these two phase optimization methods are neither necessary nor sufficient conditions of a large DA (and MA), at least in the HEPS case.

In the design of the first hybrid 7BA lattice for the HEPS [19], we matched the optics such that $-I$ transport line is reached between the centers of the two focusing sextupoles of each 7BA. In addition, we set the tunes close to (113, 41), such that every six 7BAs have a phase advance of $2n\pi+\pi/4$ in x and y plane respectively, basically satisfying the global cancellation condition in the whole ring. For this design, it was, however, found difficult to simultaneously optimize the DA and MA, even with grid scan of the multipole strengths. The compromise solution predicted an 'effective' DA of the bare lattice (considering limitation caused by low-order resonances [20]) of 2.2 mm in the y (injection) plane and an 'effective' MA of 2.4%. In addition, it was found that the coupling resonance dominates the beam dynamics, especially in horizontal plane.

In a further optimization [21] where the layout was kept the same and the linear optics were adjusted by varying only the quadrupole strengths, the chromatic sextupole strengths were optimized and the dependence of the DA and MA on the tune was investigated with the aid of number tracking. A solution promising a similar emittance and larger DA (~3.5 mm in y plane) and MA (~3%) was found, with the integer tune more away from the global cancellation condition, (116, 41).

In addition, in the global optimization of the HEPS hybrid 7BA lattice where more than 60 variables were used and the 'effective' DA and MA of the bare lattice were used as optimizing variables (another objective was the brightness), we varied all tuneable element parameters to explore the best possible solutions, while satisfying the $-I$ transportation between sextupole pairs by varying the strengths of three families of quadrupoles (they are not used as variables). Later, just for a comparison, we remove this constraint in the optimization, which allows three more variables. The original idea was to look for better solutions with optics close to but not exactly on the '$-I$ transportation' condition. However, the optimization brought us to solutions with optics far away from the '$-I$ transportation' condition (see Fig. 1), which is very different from the expectation. These solutions promise effective MA of above 3% and effective DA of up to 8 mm [22], with the natural emittance kept at the same level as in Ref. [19].
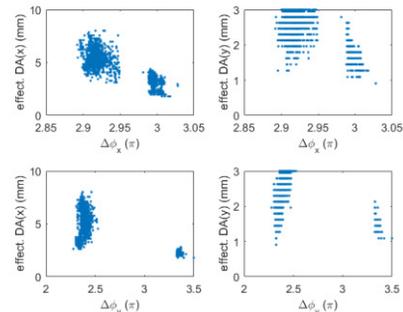
Figure 1: Phase advance between the two focusing sextupole in each 7BA of the found solutions after removing the '$-I$ transportation' condition in the optimization.

Sextupole Strengths vs. DA

One simple and straightforward intuition is that the weaker the sextupoles are, the better the nonlinear performance will be. This consideration suggests one direction of the nonlinear optimization, i.e., minimizing the sextupole strengths required to compensate for the natural chromaiticities. Nevertheless, the HEPS design experiences suggested that this may be not correct. To employ the weakest possible sextupoles is neither a necessary nor a sufficient condition of a large DA.

As mentioned above, after the first of HEPS hybrid 7BA lattice was designed, an optimization where only quadrupole strengths were varied was done to look for solutions with weaker sextupoles, and a better solution was found. Soon afterwards, when including more variables (the drift and dipole lengths and angles) in the optimization, we failed to obtain even larger DA with even lower sextupole strengths. By contrast, a comparison optimization where the DA and MA rather than sextupole strengths were used as optimizing objectives indicated that the solutions showing optimal trade-offs between emittance and nonlinear performance have stronger sextupoles [23].

This is counter-intuitive but understandable. In a limited scenario that the natural chromaticiteis are very small and the sextupoles used for chromatic correction are extremely weak, the nonlinear perturbation to the particle motion will be very weak and the DA will be very large. However, such a case will not happen in a practical DLSR design. The sextupole strengths may be reduced by a few ten percent after optimization, but cannot be reduced by one or even more orders of magnitude. This will not result in a large difference in the nonlinear dynamics.

Global Optimization with Stochastic Algorithms

All the above discussions imply that it is hard (if not impossible) to find one or a few factors that are effective in optimizing the DA. This directs to a way of lattice design and optimization, i.e., global optimization with stochastic algorithms. This is actually what we did in the most recent HEPS lattice designs.

We applied the MOGA in the HEPS design, which greatly accelerated the lattice evolution process. Nevertheless, the efficiency of MOGA optimization decreases when including all tuneable element parameters and optimizing simultaneously the linear and nonlinear dynamics. Analysis indicated that this is mainly due to the fact that the contributions of different variables are different. For instances, the quadrupole strengths affects the emittance, brightness and the DA and MA (through phase advance) as well, while the sextupoles strengths are related only to the nonlinear performance. As a result, it is necessary to breed enough diversity in the initial population; otherwise the population evolved with MOGA was usually converged to local optima rather than global optima. But in such an explorative optimizing problem, it is difficult to ensure enough diversity in the initial popula-

tion. Worse still, the MOGA itself cannot give a measure of the diversity of a population.

Later, the PSO algorithm was introduced in the HEPS design, which was found to be able to breed more diversity in the evolution of population, but with slower converging speed to the optimal Pareto front. Thus, a rational combination of PSO and MOGA was suggested, which was demonstrated to be more effective than using either of these two algorithms alone [23]. The iterative application of the PSO and MOGA in HEPS lattice design finally allows us to reach the latest hybrid 7BA lattice with antibend and superbend.

REFERENCES

[1] R. Hettel, "DLSR design and plans: an international overview", *J. Synchrotron Radiat.*, vol. 21, 843-855, 2014.

[2] Y. Jiao *et al*., "Performance comparison of different TME unit cells", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper TUPMF054, this conference.

[3] E.D. Courant, R.D. Ruth, W.T. Weng, In *Proc. AIP Conf.*, 127, p.294, 1985.

[4] A.J. Dragt, An overview of Lie methods for accelerator physics, in: Proceeding of PAC2013, Pasadena, USA, 2013, p. 1134-1138.

[5] Y. Cai *et al*., "Ultimate storage ring based on fourth-order geometric achromats", *Phys. Rev. ST Accel. Beams*, 15, 054002, 2012.

[6] L. Farvacque *et al*., "A low-emittance lattice for the ESRF", in *Proc. IPAC'13*, Shanghai, China, 2013, MOPEA008, p. 79-81.

[7] I.V. Bazarov and C.K. Sinclair, *Phys. Rev. ST Accel. Beams*, 8, 034202, 2005.

[8] L. Yang, Y. Li, W. Guo, S. Krinsky, *Phys. Rev. ST Accel. Beams*, 14, 054001, 2011.

[9] M. Borland, L. Emery, V. Sajaev, A. Xiao, Direct Methods of Optimization of Storage Ring Dynamic and Momentum Aperture, *in Proceeding of PAC'09,* Vancouver, Canada, p. 3850-3852, 2009.

[10] Z. Bai, L. Wang, and W. Li, in *Proc. of IPAC'11*, San Sebastián, Spain, p. 2271-2273, 2011.

[11] X. Pang and L.J. Rybarcyk, *Nucl. Instrum. Methods Phys. Res., Sect. A*, 741, p. 124-129, 2014.

[12] X. Huang and J. Safranek, *Nucl. Instrum. Methods Phys. Res., Sect. A*, 757, p. 48-53, 2014.

[13] H.S. Dumas, J. Laskar, *Phys. Rev. Let.*, 70, 2975, 1993.

[14] Y. Jiao *et al*., "Evolution of the lattice design for the High Energy Photon Source", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper TUPMF049, this conference.

[15] Y. Jiao *et al*., "Accelerator Physics studies for the High Energy Photon Source in Beijing", in *Proc. FLS2018*, MOP2WB01, Shanghai, China, 2018.3.

[16] G. Xu and Y. Jiao, "Towards the ultimate storage ring: the lattice design for Beijing Advanced Photon Source", *Chin. Phys. C*, 37(5), 057003 (2013).

[17] Y. Jiao and G. Xu, "PEPX-type lattice design and optimization for the High Energy Photon Source", *Chin. Phys. C*, 39(6), 067004, 2015.

[18] Y. Jiao, S.X. Fang, Q. Qin, J.Q. Wang, *Nucl. Instrum. Methods Phys. Res., Sect. A*, 566, 270, 2006.

[19] G. Xu, Y. Jiao, Y. Peng, "ESRF-type lattice design and optimization for the High Energy Photon Source", *Chin. Phys. C*, 40(2), 027001, 2016.

[20] Y. Jiao, Z. Duan, G. Xu, "Characterizing the nonlinear performance of a DLSR with the effective acceptance of the bare lattice", in *Proc. IPAC'17*, WEPAB055, Copenhagen, Denmark, 2017.5.

[21] Y. Jiao, "Improving nonlinear performance of the HEPS baseline design with a genetic algorithm", *Chin. Phys. C*, 40(7), 077002, 2016.

[22] Y. Jiao *et al.*, "Status of HEPS lattice design and physics studies", in *Proc. SAP2017*, Jishou, China, 2017.8.

[23] Y. Jiao and G. Xu, "Optimizing the lattice design of a diffraction-limited storage ring with a rational combination of particle swarm and genetic algorithms", *Chin. Phys. C*, 41(2), 027001, 2017.

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