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EVOLUTION OF THE LATTICE DESIGN FOR THE HIGH ENERGY PHOTON SOURCE*

Y. Jiao†, G. Xu, Y.M. Peng, S.Y. Chen, J.Y. Li, Q. Qin, J.Q. Wang, C.H. Yu, Key Laboratory of Particle Acceleration Physics and Technology, IHEP, CAS, Beijing 100049, China

Abstract

The High Energy Photon Source (HEPS) is a high-energy, ultralow-emittance, kilometer-scale storage ring light source to be built in China. The HEPS lattice design has been started since 2008. In this paper we will review the evolution of the HEPS lattice design over the past ten years, focusing mainly on the linear optics design and nonlinear optimization.

INTRODUCTION

In the past ten years, great progress has been made in the accelerator physics and technology studies related to the ultralow-emittance storage ring light source based on multi-bend achromat (MBA) lattice, which drives the conceptual design quickly into actual construction. Many facilities, including MAX-IV [1], Sirius [2], ESRF-EBS [3], APS-U [4], ALS-II [5], Spring-8-II [6], and many others were under design, construction, commissioning or operation, with natural emittance of one or two order of magnitude lower than available in existing third generation light sources (TGLSs). In this kind of storage ring light sources, the transverse emittances of the electron beam are already on the same level as the diffraction limit of x-rays of interest for scientific community. Thus, it was named diffraction-limited storage ring (DLSR) light source [7].

Early in 2008, a high-energy, kilometer-scale storage ring light source, originally called Beijing Advanced Photon Source and now named High Energy Photon Source (HEPS), was proposed and was planned to be built around Beijing, in the north of China [8]. Along with the progress in the field of DLSR light source, the basic lattice structure of the HEPS storage ring has been continuously evolved for about ten years, from DBA, standard 7BA, TBA, standard 7BA with high-gradient quadrupoles, hybrid 7BA with high-gradient quadrupoles, to the latest structure, hybrid 7BA with super-bends and anti-bends [9-28]. As shown in Fig. 1, without a great change of the circumference, the natural emittance was reduced by a factor of about 50, from 1.5 nm to 34 pm.

In the following, we will briefly review the design and optimization of the HEPS lattice based on different structures, where the main considerations behind each change will also be introduced.

HEPS LATTICE EVOLTUION

The original HEPS lattice [8] was a DBA lattice, which was basically a TGLS design, with a circumference of 1.2 km and a natural emittance of 1.5 nm at 5 GeV.

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† email address: jiaoyi@ihep.ac.cn

From 2008 to 2011, this DBA lattice was unchanged. Nevertheless, we kept on exploring methods of improving the machine performance, such as preliminary attempt of genetic optimization of nonlinear dynamics, development of theoretical analyser of beam dynamics, parameter optimization of the bending magnets with longitudinal gradient (LGBs) [29], studies of the so-called modified-TME (theoretical minimum emittance) unit cell [30]. These efforts, together with the inspiration of the pioneer MBA designs, e.g., MAX-IV [1] and PEP-X [31], promoted exploration of the HEPS ultralow-emittance lattices.

The first MBA lattice with a complete linear optics design and nonlinear optimization [9] was based on the standard 7BAs. This lattice has 16 superperiods, each of which consists of two 7BAs. The circumference is 1263.4 m, and the natural emittance is 75 pm.rad at 5 GeV.

To achieve a promising performance, several measures were adopted. In linear optics design, we used modified-TME unit cells with dipoles combined with horizontally defocusing gradients ($J_x > 1$), and small-aperture magnets and vacuum chambers (following the MAX-IV design). This design has alternative high- and low-beta straight sections, for the sake of efficient injection (that time we considered mainly off-axis injection with pulsed sextupoles [32]) and high-brightness emission from insertion devices (IDs). In nonlinear optimization, following Ref. [31], we matched the linear optics such that every eight superperiods forms a quasi-3rd-order achromat, which helps to approximately cancel the 3rd- and most of the 4th- order resonances. In addition, a theoretical analyzer based on Lie Algebra and Hamiltonian dynamics was developed to obtain analytical expressions of the detune, chromaticity, and the resonance driving terms with respect to the sextupole and octupole strengths (see [9] for details). We then made multi-objective genetic optimization (MOGA) with NSGA-II [33] by setting three objective functions to characterize these nonlinear driving terms. It was noted that a solution with low driving terms does not definitely result in a good nonlinear performance [34]. Thus, among the obtained optimal solutions, we verified them with numerical tracking, and chose the 'best' solution, which predicted a momentum acceptance (MA) of 3% and a dynamic aperture (DA) of 6 mm and 2.6 mm in x and y plane respectively, at the centre of the high-beta straight section. The DA basically satisfies the DA requirement for pulsed sextupole injection.

At the same time, different candidate MBA lattices were explored [10], while without deep nonlinear optimizations. In addition, we also considered approaching the diffraction limit of 1 Å hard x-ray in both x and y planes by using use damping wigglers and strong solenoids (to achieve a local round beam) [35].

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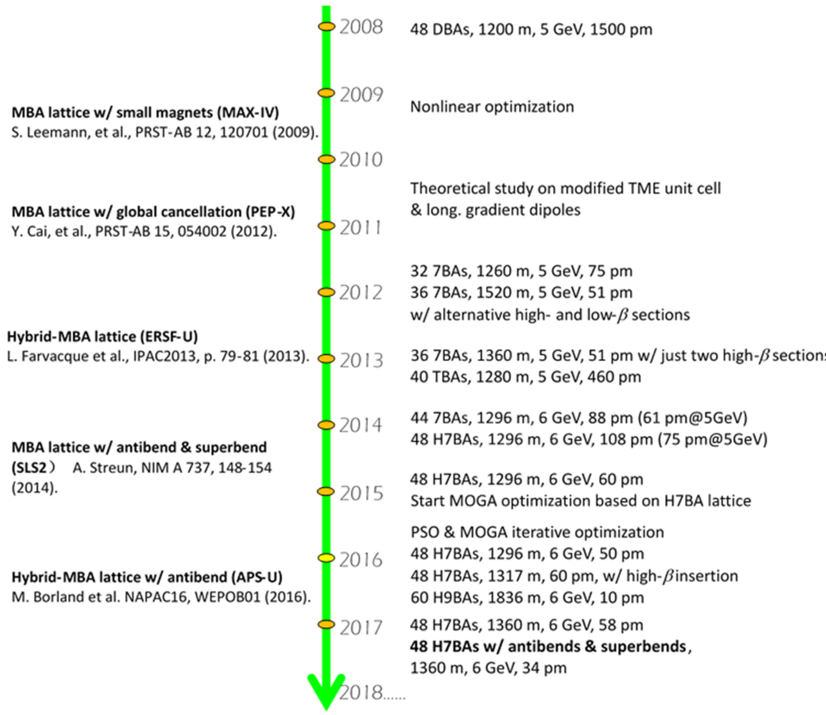

Figure 1: Evolution of the HEPS lattice over the past ten years. The figure also shows several representative DLSR designs around the world on the left side of the time axis.

In the following two years, design and optimization of the standard MBA lattice were continuously implemented [12, 15]. To increase the number of the low-beta sections for high brightness, the lattice was modified to have only a few high-beta sections. To restore the periodicity, the phase advance of the high-beta section was tuned to be same as that of a normal section, or with a difference of $2n\pi$ (n is integer). A large DA could be obtained. The MA was, however, intrinsically small. This was found because of that the difference in phase advance between two kinds of sections will deviate from $2n\pi$ as the momentum deviation increases, leading to destroyed periodicity and poor off-momentum beam dynamics. Most importantly, we found the limitation of a standard MBA lattice in emittance minimization [15]. When the natural emittance of standard MBA lattice is reduced to several tens of picometers, even if very aggressive quadrupoles are used (e.g., as in the hybrid-MBA lattice [3]), it is very difficult (if not impossible) to further decrease the emittance, otherwise impractically thick sextupoles (using conventional magnet technology) will be required to correct the rapidly increasing natural chromaticities.

Before moving to the lattice design based on the hybrid-7BA structure, there was an episode in the lattice evolution around 2013. It was considered to use a TBA lattice as the baseline [11]. In this lattice, the optics was matched such that the TME condition was exactly satisfied in the middle dipole of each TBA. A natural emittance of 460 pm at 5 GeV was reached with a circumference of 1284 m. The main consideration behind this decision is that that time we were not so confident in fabrication of the small-aperture magnets and vacuum chambers required for a DLSR light source, and we were also wondering whether the ring acceptance in the presence of practical errors is large enough for off-axis injection.

Soon afterwards, it was decided to continue on the MBA lattice design, and the nominal beam energy was changed from 5 to 6 GeV. To prepare for the application of the test facility of the HEPS (HTPS-TF, which was officially funded in 2016) whose goals were to develop the required key hardware techniques and complete the design of the HEPS project, a lattice consisting of 48 hybrid 7BAs was proposed [16], with a circumference of 1296 m and a natural emittance of 60 pm at 6 GeV.

The hybrid-MBA concept was first proposed in the ESRF upgrade project [3]. A hybrid MBA lattice is able to create dispersion bumps which facilitate compensation for very large natural chromaticities, it also adopts aggressively strong focusing which results in a compact layout as well as an ultralow emittance. A –I transportation was designed for locally cancelling nonlinearities.

Nevertheless, for the HEPS-TF baseline lattice, it was found [16] difficult to simultaneously optimize the effective DA and MA, even with $-I$ transportation between sextupole pairs, fine tuning of the phase advance of each 7BA and grid scan of the multipole strengths. The compromise solution predicted an 'effective' DA of the bare lattice (considering limitation of low-order resonances [36-37]) of 2.2 mm in the y (injection) plane and an 'effective' MA of 2.4%. Regarding the small DA, on-axis injection schemes, such as swap-out injection and longitudinal accumulation were considered (e.g., [38]).

To improve the nonlinear performance of the hybrid-7BA lattice, global optimization was performed. As a first attempt, due to limitation of computing sources, MOGA optimization of only the linear optics by varying quadrupole strengths was done, with the aim to find solutions with weaker sextupoles. A scan of the nonlinear performance with respect to the fractional tunes was done subsequently. In this way, a solution with similar emittance (59.4 pm) and better nonlinear performance was found, with the DA in the *y* plane increased to 3.5 mm and the MA increased to 3% [17].

Following basically the same way, more variables (total number ~ 26) were included in optimization, such as the drift lengths and dipole parameters. At this time, it was, however, found that the weakest possible sextupoles do not result in the largest ring acceptance. By contrast, a comparison optimization where the DA and MA were directly used as optimizing objectives indicated that the solutions predicting the largest possible DA and MA have stronger sextupoles. In addition, it was found that when applying MOGA to such an explorative optimizing problem with many variables, the results depend significantly on the degree of diversity of the initial population. Worse still, MOGA itself cannot give a measure of the diversity of a population. This makes the population easily trapped into local optima rather than global optima. We demonstrated that this difficulty can be overcome with the particle swarm optimization (PSO) (e.g., [39]), which has an intrinsic ability to breed more diversity in the evolution of the population. Studies [18-22] suggested that a rational combination of PSO and MOGA would be more effective than using either of these alone in exploring the ultimate performance of a DLSR lattice. In this way, we found solutions with even lower emittance (52 pm) and larger DA and MA (4.8 mm in the *y* plane and 3.6%) [22].

Except the optimization of the HEPS-TF baseline lattice, we also discussed the possibility of the HEPS lattice with transverse emittances reaching the diffraction limit of one Å hard x-ray (without use of damping wigglers) [24], and tried to explore candidate lattice that promises off-axis injection, by inserting a few high-beta sections in the hybrid-7BA lattice [25].

Note that, in the above hybrid-7BA lattice design and optimizations, it was assumed that the first (sixth) and the second (seventh) dipoles (they are LGBs) of each 7BA have asymmetric magnetic field profiles. In the first meeting of HEPS-TF International Advisory Committee (Dec. 2016), it was suggested to independently vary the LGB parameters to reach lower emittance (saying ~40 pm), and optimize the brightness at a specific photon energy (saying 20 keV) instead of the natural emittance.

Actually, from the beginning of the HEPS lattice optimization, we gradually accumulated computing sources. This finally made it feasible to do the global optimization with more than 60 variables, where all tuneable element parameters were varied and the effective DA and MA of the bare lattice were directly calculated and used as optimizing variables. In addition, in optimization we first kept the $-I$ transportation between sextupole pairs and then removed this constraint, which helped to find solutions in different integer tune regions from the case satisfying the $-I$ transportation, with even better nonlinear performance [40]. Studies [26] showed that for the HEPS lattice with 48 hybrid-7BAs, if satisfying only the DA requirement of on-axis swap-out injection, the HEPS ring emittance can be pushed down to ~45 pm.rad; if keeping the emittance to be around 60 pm, the DA can be larger than 8 mm.

Meanwhile, we tried to explore even better lattice structures. It was noticed that using antibend and superbend in the ultralow emittance unit cell (e.g. the SLS-II design [41]), one can greatly reduce the available minimum emittance of a storage ring. And, by adopting antibend in the APS-U hybrid-7BA lattice design [4], the emittance can be further reduced by about 30%, without paying any price in nonlinear acceptance of the ring.

Based on a thorough comparison of different ultralow emittance unit cells (see [42] for details), we replaced the middle cell of the hybrid-7BA with a unit cell having anitbend and superbend for a lower emittance. In addition, from discussions with beam line experts, we learned that there are not so many users as expected pursuing high brightness. It was then decided to look for an alternative high- and low- beta design. In this way, one can further push the beta function of one straight section down to close the optimal values for the highest possible brightness, and keep the beta function of another section to moderate values for an adequate DA for on-axis injection.

These considerations together brought about the latest HEPS lattice with a natural emittance of 34 pm [27, 28, 43], a adequate DA for on-axis injection and an MA of ~3% at the injection point. In this design, the superbends will be used for bending magnet beam lines. Studies indicate that once the total bending angle and length is not changed, the peak field of the superbend can be varied to emit x-rays with different critical photon energy for users, while causing little perturbation to the global linear optics and nonlinear performance of the ring.

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