ESRF-type lattice design and optimization for the High Energy Photon Source*

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Abstract: A new generation of storage ring-based light sources, called diffraction-limited storage rings (DLSRs), with emittance approaching the diffraction limit for multi-keV photons by means of multi-bend achromat lattices, has attracted extensive studies worldwide. Among various DLSR proposals, the hybrid multi-bend achromat concept developed at the European Synchrotron Radiation Facility (ESRF) predicts an effective way of minimizing the emittance while keeping the required chromatic sextupole strengths to an achievable level. For the High Energy Photon Source planned to be built in Beijing, an ESRF-type lattice design consisting of 48 hybrid seven-bend achromats is proposed to reach emittance as low as 60 pm·rad with a circumference of about 1296 m. Sufficient dynamic aperture, allowing vertical on-axis injection, and moderate momentum acceptance are achieved simultaneously for a promising ring performance.

Keywords: diffraction-limited storage ring, hybrid multi-bend achromat, High Energy Photon Source

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1 Introduction

Along with the continuous advance in accelerator technology and unceasing pursuit of higher quality photon flux, worldwide efforts are being made to push the brightness and coherence beyond the existing third generation light sources, by significantly reducing the emittance to approach the diffraction-limit for the range of X-ray wavelengths of interest to the scientific community. Such new-generation rings are usually called diffraction-limited storage rings (DLSRs). An international overview of DLSR designs and plans can be found in Ref. [1]. To achieve an ultralow emittance (e.g., several tens of pm·rad) with the least possible cost, multi-bend achromats (MBAs) with a combination of compact magnets and strong focusing quadrupoles are generally adopted in DLSR designs.

The MAX-IV [2] first adopted small-aperture, high-gradient magnets (e.g., quadrupole gradient of up to 50 T/m with bore radius of 12.5 mm) and small-dimension vacuum chambers coated with non-evaporable getter material in its 7BA design. With these advanced technologies, it was able to realize an emittance of about 300 pm·rad within a circumference of 528 m for a 3 GeV beam. Following MAX-IV, MBA lattice proposals have been raised for a number of facilities being designed, constructed, or upgraded, including Sirius [3], PEP-X [4], ESRF-U [5], APS-U [6], ALS-II [7], Spring-8-II [8] and the High Energy Photon Source (HEPS, originally named BAPS [9–10]). In these proposals, many measures have been taken to decrease the emittance to below 100 pm·rad while keeping the beam dynamics robust and satisfactory. For instance, vertical focusing [11] or longitudinal gradient [12] is combined into the dipole to shorten the unit cell length and to help minimize the emittance; a high-field (2–3 T) super bend [3] or 3-pole wiggler [5] is inserted at (or close to) the center of the MBA as a hard X-ray source; phase optimization is performed to improve the nonlinear beam dynamics, either by constructing a third-order geometric achromat with several identical MBAs [4] or by employing $-I$ transport between sextupole pairs in a single MBA [5]; the quadrupole gradient is further enhanced to approach 100 T/m [5] by using high-permeability pole material or permanent magnet material near the poles to reduce saturation, for a more compact magnet design and MBA layout; moreover, as illustrated in the so-called hybrid-MBA concept [5] first proposed at ESRF, a dispersion bump is created between the outer two dipoles for a more efficient chromatic correction than available in a normal MBA.

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HEPS is a kilometer-scale, 5–6 GeV, ultralow-emittance storage ring-based light source, planned to be built in Beijing. Various lattice designs and relevant studies have been performed for HEPS since 2010 [9–10, 13–20]. Since HEPS is a new machine, it has great flexibility in the choice of the ring parameters, e.g., the circumference. It is known that with a larger circumference it will be easier to achieve an ultralow emittance as well as satisfactory beam dynamics. However, it is necessary to reduce the circumference as much as possible so as to reach a relatively low budget. As a compromise and based on other considerations (e.g., to achieve a harmonic number of 2160 for ∼500 MHz RF system and to keep the capability of the storage of beam at 6 GeV), the circumference has recently been determined to be around 1296 m and the lattice cell structure is chosen to be 7BA instead of double-bend or triple-bend achromat.

A PEPX-type lattice [10] has been proposed for HEPS by using 44 normal 7BAs, with a circumference of 1294.2 m and emittance of 90 pm·rad for a 6 GeV beam. With delicate optimization, a dynamic aperture (DA) larger than the physical aperture and promising off-axis pulsed-sextupole injection, a momentum acceptance (MA) as large as 3% for a long enough lifetime can be obtained in two separate modes, which are only different in sextupole and octupole strengths and thus can be easily switched from one to the other. Nevertheless, it is very difficult to further push down the emittance with this type of design; otherwise impractically high-gradient or thick sextupoles will be required to correct the increasing natural chromaticities.

As will be shown in Sec. 2, with an ESRF-type lattice design consisting of 48 hybrid-7BAs, a lower emittance of 60 pm·rad can be reached with a similar circumference. In addition, thanks to the dispersion bump, the difficulty of the chromatic correction in the PEPX-type design can be greatly mitigated. The nonlinear beam dynamics is studied in Sec. 3, and it appears feasible to obtain sufficient DA and MA for vertical on-axis injection and moderate lifetime simultaneously. Conclusions are given in Sec. 4.

2 Linear optics design

In the design of a hybrid-7BA, several key demands should be satisfied. First, for the central three unit cells, quadrupoles with strong horizontal focusing and dipoles combined with vertical focusing gradients are required to minimize the emittance and the cell length. Second, it needs to create two symmetric dispersion bumps in the gaps between the outer dipoles (with as large a dispersion as possible between the first and the second, and between the sixth and the seventh dipoles) where sextupoles are installed to correct the natural chromaticity. Third, the phase advance between each pair of sextupoles in a hybrid-7BA should be at or close to π, thus eliminating most of the undesirable effects of sextupoles. Fourth, it needs to introduce a longitudinal gradient into the outer dipoles (with stronger bending field at the part with greater distance from the dispersion bump), to increase the dispersion at the sextupole and to further decrease the emittance.

Based on the above, the hybrid-7BA for HEPS is designed in two steps. First, the case without longitudinal gradient combined in the outer dipoles is considered. The linear optics is matched such that the first three demands mentioned above are satisfied. To make a practical design, as many constraints on the magnets and drift spaces as possible are included in the optics matching. For instance, it is required that the maximum focusing gradient is 80 T/m for the quadrupoles in the central three unit cells, and 52 T/m for the others (the corresponding pole face fields are 1 T and 0.65 T, respectively, with bore radius of 12.5 mm); for the central three combined-function dipoles, the bending radii should be larger than 40 m and the gradients should be smaller than 48 T/m, with pole face gap of 38 mm; the length of the long straight section for insertion devices (IDs) or injection is fixed to 6 m; enough drift spaces are preserved for sextupoles, octupoles, diagnostics, correctors, and for fast feedback kickers (in the drift between the first and the second quadrupoles and that on the mirror side, more than 0.3 m) and a 3-pole wiggler (in the drift next to the third or the fifth dipole, more than 0.35 m) as well. In addition, the lengths of quadrupoles are minimized, while keeping the required gradients well below their upper limits. Finally, a hybrid-7BA of 26.992 m is reached, with the layout and the optical functions (solid curves) presented in Fig. 1.

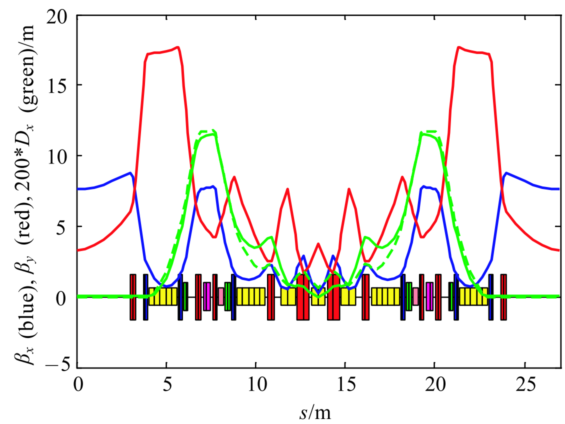

Fig. 1. (color online) Layout and optical functions of the hybrid-7BA designed for HEPS, without (solid curves) and with (dashed curves) longitudinal gradient combined in the outer dipoles.

In the second step, longitudinal gradient is introduced into the outer dipoles and the emittance is further minimized. Each of the outer dipoles is split into five slices, which are considered to have different bending radii. Moreover, the bending angles are redistributed among the seven dipoles. With the other parameters unchanged, the analytical expression of the emittance is derived following Ref. [21] and is then minimized. As a result, the emittance is decreased from 100 pm·rad to 60 pm·rad. Since rectangular dipoles are used in the lattice and their lengths are unchanged, the Courant–Snyder parameters remain the same. The variations in the bending radii of dipoles cause only a small change in dispersion functions, with the dispersion increasing slightly from 5.7 cm to 5.85 cm near the center of the dispersion bump (see the dashed curve in Fig. 1).

Three families of sextupoles (one family with horizontal focusing, SF, and the other two with vertical focusing, SD1 and SD2) are used for chromatic correction and are all located in the dispersion bump, where the relative high dispersion helps control the sextupole gradient and length to a reasonable level, i.e., below 6000 T/m^2 (the corresponding pole face field is 0.47 T with bore radius of 12.5 mm) and ∼0.3 m, respectively. Forty eight such hybrid-7BAs comprise the ring, with the main parameters listed in Table 1.

Table 1. Main parameters of the ESRF-type lattice for HEPS.

parameters	values
energy E_0/GeV	6 (5)
circumference C/m	1295.616
horizontal damping partition number J_x	1.38
natural emittance ε_0/(pm·rad)	60 (41.7)
number of hybrid-7BA achromats	48
maximum quadrupole gradient/(T/m)	80
maximum sextupole gradient/(T/m^2)	6000
number/length of ID straight sections/m	48/6
beta functions in ID straight section (H/V)/m	7.6/3.3
working point (H/V)	113.20/41.28
natural chromaticity (H/V)	−149/−128
energy loss per turn U_0/MeV	1.995
damping times $(x/y/z)$/ms	18.8/26.0/16.0
RF voltage $V_{\rm rf}$ /MV	6
RF frequency $f_{\rm rf}$ /MHz	499.8
harmonic number	2160
energy spread σ_δ	7.99×10^{-4}
bunch length σ_z/mm	2.07
momentum compaction $\alpha_{\rm p}$	3.67×10^{-5}

3 Nonlinear optimization

DA and MA are the two most important objectives of the optimization of nonlinear beam dynamics. The DA (for on-momentum particles) is most relevant to the injection efficiency, while the MA is most relevant to the Touschek lifetime, which is the main limitation of the available beam lifetime in a DLSR. Next we will show the study results of the nonlinear beam dynamics for this design.

As mentioned, by means of the dispersion bump and local cancellation scheme, the chromatic sextupole strengths and the geometric aberrations induced by the sextupoles have been controlled to a relatively low level. However, associated with the ultralow emittance and small beta functions in the long straight section, it is still extremely difficult, if not impossible, to achieve DA of the order of 10 mm to accommodate off-axis injection. Nevertheless, the requirement on DA can be greatly reduced with an on-axis 'swap-out' injection scheme [22], in which the already-stored bunches are kicked out and replaced with fresh bunches from the booster. Based on the above, the injection scheme for the ESRF-type design is chosen to be on-axis 'swap-out' injection in the vertical plane by use of stripline kickers. Details of the injection system, however, will be discussed elsewhere.

On the other hand, to save as much space as possible to accommodate various kinds of hardware systems, except for the three families of sextupoles, only one family of octupoles (with vertical focusing, OF) is used to correct the high-order aberrations, especially the vertical detune terms. It is known that at least two families of sextupoles with opposite focusing are needed to correct the natural chromaticity to a positive value (fixed to [0.5, 0.5] in this study). If the strength of one family of vertical-focusing sextupoles (e.g., SD2) is determined, there is a unique solution for the other two families (SD1 and SF). There are only two free variables left, i.e, $K_{\rm SD2}$ and $K_{\rm OF}$, and thus it is possible to make a global scan of all the possible settings in the ($K_{\rm SD2}$, $K_{\rm OF}$) space in a reasonable computing time.

Since the beam injection in the vertical plane is being considered, the goal is to maximize the vertical ring acceptance. To this end, the vertical DAs with all possible sets of ($K_{\rm SD2}$, $K_{\rm OF}$) are specifically calculated using the AT program [23], with the results shown in Fig. 2. Frequency map analysis [24] is also performed to analyze the stability of the motion. It reveals that since only the ideal lattice (without any error) is considered, the particle motion can cross the fatal first and second-order resonances without loss, which may cause an overestimation of the available ring acceptance for the injected beam. To solve this problem, the vertical 'effective' DAs which promise only the motions with fractional tunes within [0, 0.5] are calculated and also presented in Fig. 2. It appears that the maximum vertical 'effective' DA is about 4 mm and occurs around ($K_{\rm SD2}$, $K_{\rm OF}$) = (−150 m^{-3}, −5000 m^{-4}).

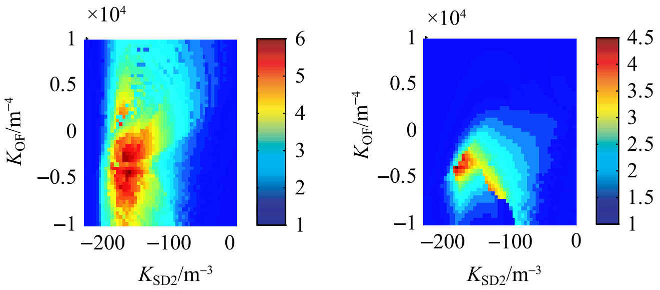

Fig. 2. (color online) Vertical DAs (left) and vertical 'efficient' DAs (right) with all possible sets of (K_{SD2}, K_{OF}). Different colors represent different DA sizes, in units of mm.

A similar scan is also performed for the MA, with the results shown in Fig. 3. In the calculation, it is assumed that the longitudinal dynamics is well optimized and the MA is limited by the transverse dynamics, or to be more specific, the MA is determined by (the absolute value of) the momentum deviation that makes the fractional tune very close to or exactly at 0 or 0.5, in either x or y plane. One can see that the MA of 3% can be achieved around (K_{SD2}, K_{OF}) = (−100 m^{-3}, −1000 m^{-4}).

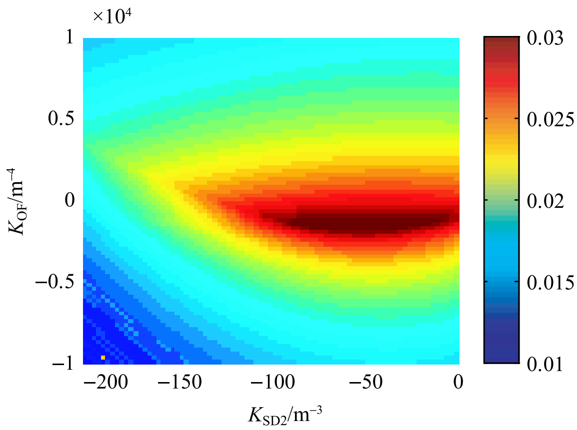

Fig. 3. (color online) MAs with all possible sets of (K_{SD2}, K_{OF}). Different colors represent different MA values, from 1% to 3%.

Figure 4 shows the contour plots of both the vertical 'effective' DA and the MA in the (K_{SD2}, K_{OF}) space. It seems impossible to find a solution that optimizes both objectives simultaneously. Tradeoffs between the two objectives should be made. Finally, a solution with (K_{SD2}, K_{OF}) = (−120 m^{-3}, −1600 m^{-4}) is chosen to provide a vertical 'effective' DA of ∼2.2 mm and an MA of ∼2.4%. The on-momentum 'effective' DA and the corresponding frequency map are shown in Fig. 5, and the off-momentum DAs are shown in Fig. 6. The coupling resonance $2\upsilon_x - 2\upsilon_y = 48\times3$ imposes a strong perturbation on the motions in the horizontal plane between [1.1, 1.4] mm, but has very weak impact on the motions in the vertical plane. For this solution, the intrabeam scattering (IBS) and the Touschek lifetime are evaluated by assuming the electrons are evenly distributed in 1800 buckets of the ring, with the results listed in Table 2. It appears that increasing the transverse coupling will help reduce the IBS effect and increase the Touschek lifetime. Nevertheless, even with a coupling factor of 2%, the Touschek lifetime is still very low, 0.6 h with beam current of 200 mA. To achieve a long enough lifetime, it is necessary to further enlarge the MA, and/or the bunch length (using harmonic cavities [19]) in future optimization.

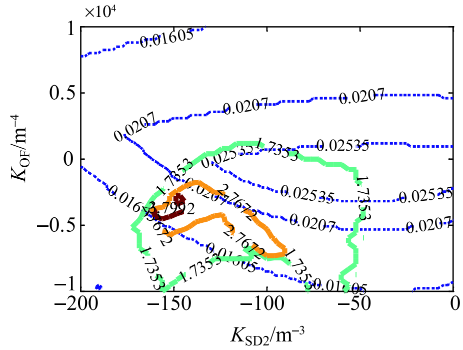

Fig. 4. Contour plots of the vertical 'effective' DA (in units of mm, solid curves) and MA (dotted curves) in the (K_{SD2}, K_{OF}) space.

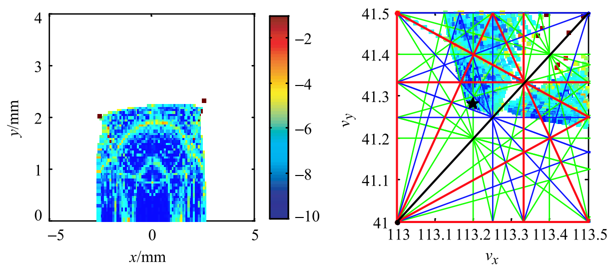

Fig. 5. (color online) The 'effective' on-momentum DA and frequency map obtained after tracking over 1024 turns for the HEPS lattice design with (K_{SD2}, K_{OF}) = (−120 m^{-3}, −1600 m^{-4}). The colors, from blue to red, represent the stabilities of the particle motion, from stable to unstable.

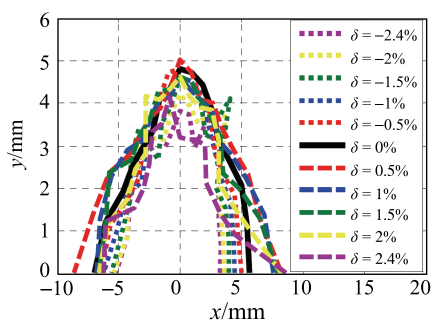

Fig. 6. (color online) Off-momentum DAs obtained after tracking over 1024 turns for the HEPS design with (K_{SD2}, K_{OF}) = (−120 m^{-3}, −1600 m^{-4}).

Table 2. Evaluation of the IBS-induced emittance growth and Touschek lifetime

	coupling κ= 1%	coupling κ=2%
$\varepsilon_x/\varepsilon_y$ at I = 100 mA/(pm·rad)	82.8/0.81	75.0/1.50
$\varepsilon_x/\varepsilon_y$ at I = 200 mA/(pm·rad)	92.7/0.93	84.6/1.70
τ_{Tou} at I = 100 mA/h	0.91	1.21
τ_{Tou} at I = 200 mA/h	0.45	0.60

4 Conclusion

In this paper, we have presented an ESRF-type design for HEPS. The linear optics is designed such that the requirements of the ultralow low emittance, effective chromatic correction, and enough drift spaces for various hardware systems are fully considered and basically satisfied. By using one family of octupoles to minimize the nonlinear driving terms caused by the sextupoles, a vertical effective DA of 2.2 mm and MA of about 2.4% can be achieved.

The presented design is not an optimal result, but can basically meet the requirements of vertical on-axis injection and a reasonable beam lifetime. This design has therefore been adopted as the baseline of the HEPS test facility. Continuous optimizations are under way to improve both the linear optics and the nonlinear beam dynamics.

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