CANDIDATE HEPS LATTICE DESIGN WITH EMITTANCES APPROACHING THE DIFFRACTION LIMIT OF HARD X-RAYS*

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Abstract

The High Energy Photon Source is a 6-GeV, kilometre-scale storage ring light source to be built in Beijing. A lattice of the storage ring was proposed, consisting of 48 hybrid 7BAs, and having a natural emittance of 60 pm and a circumference of ~1.3 km. In this paper, we discuss the possibility of further reducing the emittance to approach the diffraction limit of hard X-ray with 'typical' wavelength of 1 Å. We introduce the considerations on the choice of lattice structure and circumference, and concrete lattice 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, 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 $\lambda/4\pi \sim 8$ pm.

As is known, under 'zero-current' condition, the sum of horizontal and vertical emittances in an electron storage ring, $\varepsilon = \varepsilon_x + \varepsilon_y$ is equal to ε_0, the natural emittance of the ring. On the other hand, the intrabeam scattering (IBS) is one of the most significant collective effects in a DLSR. At a high beam current, e.g., 100 or 200 mA, the IBS effect will cause non-ignorable emittance growth, causing $\varepsilon > \varepsilon_0$. Thus, to achieve ε of ~16 pm, the lattice should be designed with a natural emittance sufficiently below 16 pm.

Nevertheless, recent DLSR proposals barely push the natural emittance to such a small level, due to more and more stringent error tolerance and increasing difficulty in nonlinear optimization when decreasing the emittance. For the High Energy Photon Source (HEPS), a 6-GeV, kilometre-scale storage ring light source to be built in Beijing, China, after several iterations in the past few years, we obtained a lattice (see Ref. [2] and references therein) for the storage ring. It consists of 48 hybrid 7BAs, and has a circumference of 1295.6 m and a natural emittance is ~ 60 pm (denoted as *60-pm lattice* hereafter). This lattice was used as the baseline of the R&D project for HEPS, HEPS test facility. The optical functions along a 7BA and its layout are shown in Fig. 1.

Meanwhile, the lattice is continuously optimized, with the goal of finally finding an optimal design for the HEPS project. Recent studies indicated that for this lattice with the same lattice structure and similar circumference, it is feasible to further reduce the natural emittance to ~40 pm, but impossible to achieve ε_0 as low as 16 pm.

Since the HEPS is a green-field machine, there are not strong constraints on the lattice design except the budget (if there is one). To achieve a lattice design with a natural emittance around or lower than 16 pm is a direction of the lattice design and optimization. In the following, we will first present estimation of the required circumference to realize such a low emittance, and later introduce candidate lattice designs.

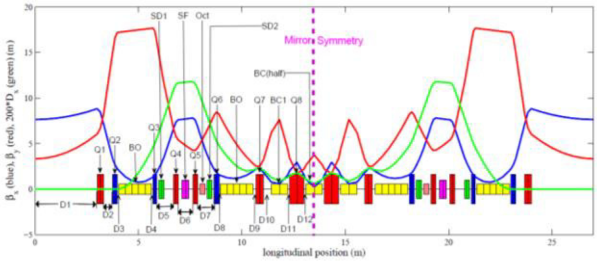

Figure 1: Optical functions along the hybrid 7BA of the 60-pm lattice.

CIRCUMFERENCE ESTIMATION

To design a practical lattice with ε_0 of about 16 pm, the hybrid MBA is a good candidate of the lattice structure, due to its excellent ability of controlling the sextupole strengths while decreasing the emittance. Another question arises then that with a hybrid MBA lattice, how large a ring is needed to achieve such a low emittance. To answer this question, we did a rough estimation of the required circumference based on the present HEPS 60-pm lattice and the emittance formula [Eq. (1) below].

In a storage ring with uniform dipoles, the horizontal natural emittance ε_0 can be written of the form

$$\varepsilon_0 = C_q \gamma^2 \frac{F(type)}{J_x} \theta^3 . \qquad (1)$$

where $C_q = 3.83 \times 10^{-13}$ m, γ is the Lorenz factor, $J_x \sim 1$ is the horizontal damping partition number, $\theta = 2\pi/N_d$ is the bending angle of the dipole, N_d is the number of dipoles. The F factor depends on the lattice type. When the optical functions within dipoles are exactly on the conditions for theoretical minimum emittance (TME), the F factor reaches it minimum values, e.g., ~0.065 and 0.034 for a DBA and a 7BA, respectively.

From Eq. (1), one can calculate the theoretical minimum emittance $\varepsilon_{\mathrm{TME}}$ for a specific number of dipoles,

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when the beam energy is fixed. In a practical lattice design, the situation is usually not exactly the same as the ideal case assumed for Eq. (1), e.g., the dipoles do not have equal bending angles, and/or are combined with transverse or longitudinal gradients. However, this equation can still serve as a standard to check the emittance-reduction efficiency of different lattices.

For the 60-pm 7BA lattice, N_d = 48*7 = 336. From Eq. (1), we get $\varepsilon_{\mathrm{TME}}$ = 11.7 pm. On the other hand, experience indicates that the available emittance of this lattice is in the range of 40~60 pm. The factor of the actual emittance over $\varepsilon_{\mathrm{TME}}$ is 3.4~5.1.

Assuming this factor remains the same for hybrid-MBA lattices, for a hybrid-7BA lattice with ε_0 of 16 (or 10) pm, the corresponding $\varepsilon_{\mathrm{TME}}$ is 3.1~4.7 (or 2.0~3.0) pm. And from Eq. (1), this corresponds to N_d of 455~522 (or 533~610), and the number of 7BAs of 65~74 (or 76~88). Assuming the length of 7BA also keeps the same as the 60-pm lattice (27 m), the required circumference can be estimated, i.e., 1.75~2.0 km (or 2~2.4 km).

Similarly, we estimate the required circumference of a hybrid-9BA lattice. In this case, the main difference is that a 9BA should have a larger length, because of two more unit cells compared to a 7BA. The length of a unit cell is assumed to be 2 m, so a 9BA is about 31 m. For a hybrid-9BA lattice with ε_0 of 16 (or 10) pm, the required circumference is 1.55~1.8 km (or 1.8~2.0 km).

From the above estimation, if using a hybrid MBA lattice to achieve emittances that approach the diffraction-limit of hard X-ray of 1 Å, 1.8 to 2.0 km seems to be a feasible circumference range. Another consideration for the choice of circumference is that the harmonic number (for 499.8 MHz RF) should be a product of as many small prime numbers as possible. Finally, we choose 1872 m and 1836 m as the candidate circumferences.

POSSIBLE LATTICE OPTIONS

A hybrid-7BA linear lattice has been designed, with a circumference of 1872 m and a natural emittance of 16.6 pm (denoted as *16.6-pm lattice* hereafter). It consists of 64 hybrid-7BAs. Each 7BA has a length of 29.25 m, and provides a 6-m straight section. The optical parameters along the 7BA are shown in Fig. 2. In spite of strong focusing, longer longitudinal dipoles (and hence longer 7BA length) are used in this lattice to obtain almost the same dispersions at sextupoles as those of the 60-pm lattice. Although detailed nonlinear optimization is not finished yet, we expect that the sextupole strengths required for chromaticity correction will be similar to those of the 60-pm lattice, and it is feasible to obtain large enough dynamic aperture (above 1 mm) for on-axis injection. Nevertheless, it is found difficult to further reduce the emittance of this lattice, e.g., to be about or smaller than 10 pm.

We also consider the case with the lattice structure changed from 7BA to 9BA, and in order to keep the same circumference, i.e., 1872 m, with the number of achromats changed from 64 to 60. Each 9BA has a length of 31.2 m. Compared to the 16.6-pm 7BA design, since more dipoles are used in this case (540 vs. 448), we expect that it is feasible to reach lower emittance, however, with a price of a shorter total length of long straight sections (360 m vs. 384 m, assuming each 9BA also provides a 6-m long straight section).

A similar case is also considered, with 60 hybrid 9BAs as well but slightly shorter circumference, i.e., 1832 m. Each 9BA has a length of 30.6 m.

The possible cases with lattice structure of hybrid 9BA are summarized below,

Case A: 60 hybrid 9BAs, with circumference of 1872 m, each 9BA length of 31.2 m, and total long straight sections length of 360 m,

Case B: 60 hybrid 9BAs, with a circumference of 1836 m, each 9BA length of 30.6 m, total long straight sections length of 360 m.

We did comparison studies, which indicated that a 30.6 m achromat length is long enough for emittance minimization; further increase in achromat length (e.g., to 31.2 m) is of little benefit to further reduction in emittance. Thus, in the following we will consider only the *Case B*.

In future, based on *Case B*, one can replace four 6-m straight sections with four 15-m straight sections and adjust the optics of the 15-m straight sections to restore the lattice symmetry. In this way, the lattice will have the same circumference as the 16.6-pm 7BA lattice, but promise lower emittance and even longer total length of long straight sections (396 m vs. 384 m).

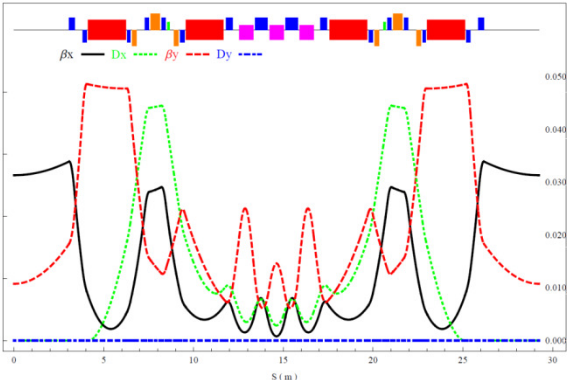

Figure 2: Optical functions along the hybrid 7BA of the 16.6-pm lattice.

HYBRID 9BA LATTICE DESIGN

The hybrid 9BA lattice is designed with a combination of multi-objective particle swarm optimization (MOPSO) and multi-objective genetic algorithm (MOGA).

In Ref. [3], based on the 60-pm lattice, we have demonstrated an effective way to evolve diverse solutions showing optimal balance between different performance parameters from an existing lattice. The key is to evolve a large enough population with MOPSO and MOGA in a successive and iterative way. Due to limited space, in the following we will briefly introduce the optimization process and introduce one typical solution, and leave details presented elsewhere.

At the beginning, we somewhat arbitrarily generate 9BA lattices based on the 60-pm 7BA lattice. The optics of one 9BA is shown in Fig. 3.

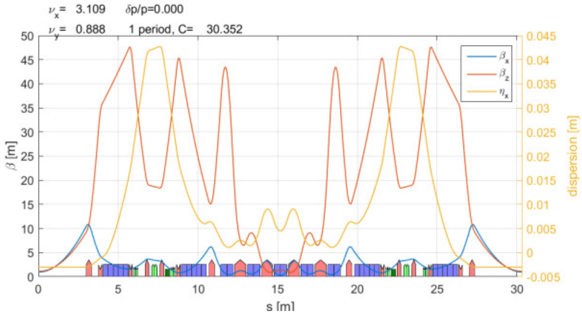

Figure 3: Optical functions of the 9BA generated from the 7BA of the 60-pm lattice.

We first do optimizations mainly on the linear optics, with the aim to quickly obtain many different combinations of element parameters resulting in low emittance in the variable space with a large number of dimensions. The found solutions are then used as the initial population of new optimizations where the linear optics and nonlinear dynamics are simultaneously optimized.

In the latter optimization, sextupoles and octupoles are added in the lattice, and the effective dynamic aperture (DA) and momentum acceptance (MA) of the bare lattice (see Ref. [4] for a detailed discussion on the effective DA and MA) are calculated to construct an optimizing objective. Another objective is set to the brightness at the photon energy of 20 keV instead of the emittance.

In addition, in the optimization it is allowed to independently adjust the gradients of mirrored quadrupoles of the 9BA, which promises different beta functions in adjacent long straight sections. In this way, in one long straight section, one can push the beta functions to as low as close to 1 m to maximize the brightness, while in another long straight section, one can realize moderate beta functions to obtain effective DA of larger than 1 mm, for the sake of efficient on-axis injection. Such a design philosophy has been applied in other light source designs, but is especially important and necessary to the lattice design with such an ultralow emittance.

After several iterations of PSO and MOGA algorithms, we obtained solutions showing good balance between the brightness and the ring acceptance.

The optics along a 9BA of one typical solution with a natural emittance of 10 pm is shown in Fig. 4. The available brightness is 5 times higher than that of the 60-pm lattice. With linear chromaticities of (+5, +5), the effective DAs are larger than 1 mm in both *x* and *y* plane (see Fig. 5), and the tunes are well within the nearby integer and half integers for a large range of momentum deviation (see Fig. 6).

CONCLUSION

In this paper, we present the feasibility study of designing a hybrid MBA lattice with emittances approaching the diffraction limit for hard X-ray of 1 Å. It appears feasible to use a circumference of ~1.8 km to achieve a natural emittance of around 10 pm while having large enough DA for on-axis injection. It is worth mentioning that there are other possible lattice options to achieve such a low emittance, e.g., using hybrid MBAs with anti-bends may allow a shorter circumference. Besides, we demonstrate again that using a rational combination of PSO and MOGA algorithms, one can evolve satisfying lattices from an arbitrary initial design.

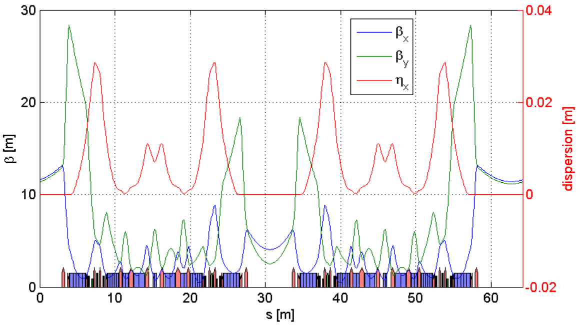

Figure 4: Optical functions of the 9BA for one 10-pm lattice obtained from MOGA and PSO evolutions.

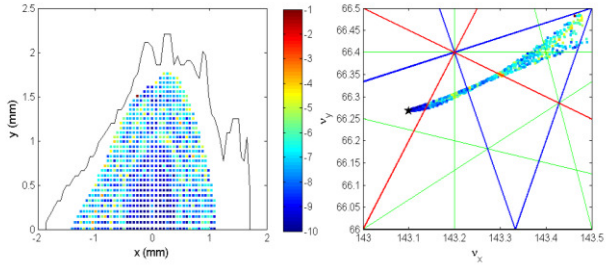

Figure 5: Effective DA and frequency map for the 10-pm 9BA lattice, the black curve on the left plot represent the DA (traditional definition) of the bare lattice.

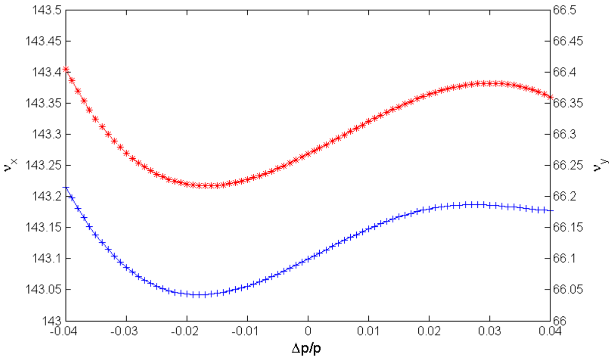

Figure 6: Chromatic curve for the 10-pm 9BA lattice.

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