LATEST DESIGN AND OPTIMIZATION OF THE PEPX-TYPE LATTICE FOR HEPS*

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Abstract

Recently the so-called diffraction limited storage ring (DLSR) with emittance around or below 100 pm.rad has attracted worldwide interest and R&D efforts. It has been proposed to build a DLSR in Beijing, named High Energy Photon Source (HEPS). In this paper, we present a latest PEPX-type lattice design of the HEPS storage ring with beam energy of 6 (or 5) GeV and horizontal natural emittance of 88 (or 61) pm.rad. Nonlinear dynamics optimization has been done to ensure an efficient injection and a long enough Touschek lifetime.

INTRODUCTION

Along with the progress in accelerator technology and the growing requirements of brighter photon flux, a new generation of storage ring-based light source, called diffraction-limited storage ring (DLSR), with emittance approaching the diffraction limit for multi-keV photons by using the multi-bend achromat lattice, has attracted worldwide and extensive studies of several laboratories, and been seriously considered as a goal of upgrading the existing facilities in the imminent future (see Ref. [1] for an international overview).

To control the ring circumference to a kilo-meter scale or smaller, and meanwhile to minimize the emittance as much as possible, multi-bend achromats with compact layout are usually adopted in DLSR designs. To reduce the emittance to a very small value, e.g., several tens of pm.rad, strong quadrupoles and sextupoles are essentially required for providing transverse focusing and chromatic correction. The nonlinearities induced by the sextupoles, if not well controlled, may lead to a poor performance of the light source. Thus, a delicate optimization of the beam dynamics is necessary to obtain sufficient dynamic aperture (DA) and momentum acceptance (MA) for an efficient injection and a long enough Touschek lifetime. It has been emphasized since one decade ago [2] that nonlinear optimization and linear matching are coupled, and phase optimization helps to minimize the nonlinear effects. For a DLSR, phase optimization indeed becomes an indispensable tool for achieving a satisfying ring performance. The PEPX design [3] demonstrates that by designing the lattice based on the 'third-order achromat' concept and with a special design of high-beta injection straight section, one can achieve sufficient acceptance for an off-axis injection. For the High Energy Photon Source (HEPS) planned to be built in Beijing, PEPX-type lattice has been designed and continuously improved. A PEPX-type lattice consisting of thirty two 7BAs and thirty six 7BAs have been designed and optimized [4-5]. In this paper, we report the latest PEPX-type design for HEPS, and discuss the main issues relevant to the linear optics design and nonlinear optimization.

LINEAR OPTICS

Most recently, the HEPS lattice is required to be designed with a fixed circumference of C = 1296 m (with +/–3 m varying range) to obtain a harmonic number of 2160 (for ~500 MHz RF cavities), and with the feasibility of ramping the beam energy from 5 to 6 GeV in a future upgrade. In addition, it was noticed that the available multipole gradient can be further enhanced based on the normal design of a small-aperture magnet (e.g. from ~50 T/m [6] to ~100 T/m [7] for quadrupole), if using high-permeability pole material (e.g. vanadium permendur) or permanent magnet material near the poles to reduced saturation. According to the above considerations, a new version of the PEPX-type lattice consisting of forty four 7BAs is designed, with ε_0 = 88 (or 61) pm.rad for 6 (or 5) GeV and C = 1294.2 m.

In the linear optics design, modified-TME unit cells [8] with horizontally defocusing gradient combined in the dipole (resulting in $J_x > 1$ for even lower emittance) are adopted, resulting in a compact layout with the cell length of 3 m, as shown in Fig. 1. In each unit cell, a 0.4-m space is reserved to accommodate diagnostics and correctors. Finally a standard 7BA with length of ~ 29 m and with a 5-m straight section for insertion device (ID) is reached, with the layout shown in Fig. 2. For the forty standard 7BAs, the phase advance of each is chosen to be $\mu_x = 4\pi + \pi/4 + \delta\upsilon_x*\pi/20$ and $\mu_y = 2\pi + \pi/4 + \delta\upsilon_y*\pi/20$ (with $\delta\upsilon_x$ and $\delta\upsilon_y$ being the decimal portions of the nominal working point), such that every eight standard 7BAs constitute a quasi-3rd-order achromat.

On the other hand, the other four 7BAs are designed to provide 10-m long straight sections to accommodate the injection devices and RF cavities, but without any sextupole/octupole (see Fig. 3). The phase advance of each special 7BA is chosen to $2n\pi$ (n is integer), which yields an identity linear transformation and hence restore the periodicity.

The main parameters of this design are summarized in Table 1.

It is worth mentioning that the special design of the injection section causes intrinsic sensitivity of the ring optics to the momentum deviation (hereafter denoted by δ), and hence increases the difficulty in pursuing for a large enough MA. Nevertheless, in the next section, we will show that, by using multi-families of harmonic sextupole and octupoles and with delicate optimization, large DA or large MA can be obtained with separate

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modes, which are different only in sextupole/octupole strengths and hence can be easily switched from one to another.

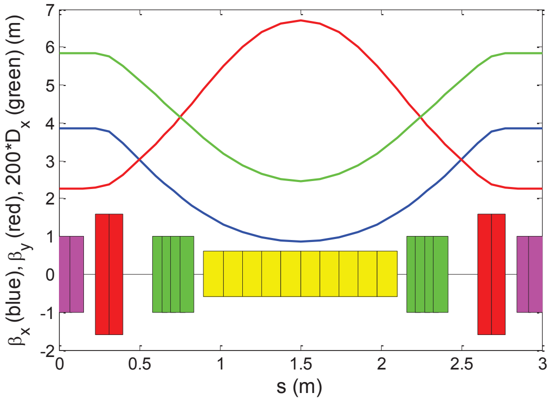

Figure 1: Layout and optical functions of the 3-m unit cell in middle of the standard 7BA, for the latest version of the PEPX-type lattice for HEPS.

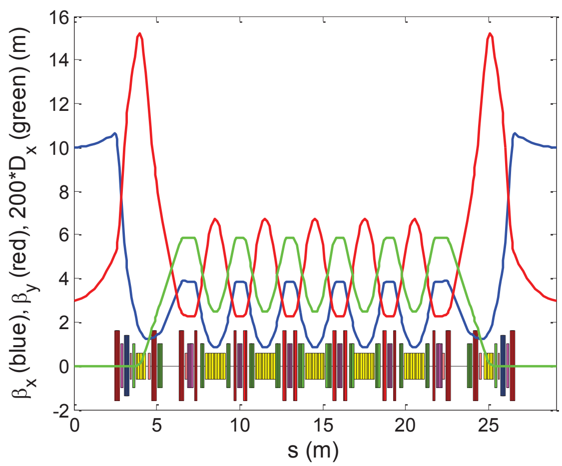

Figure 2: Layout and optical functions of a standard 7BA, for the latest version of the PEPX-type lattice for HEPS.

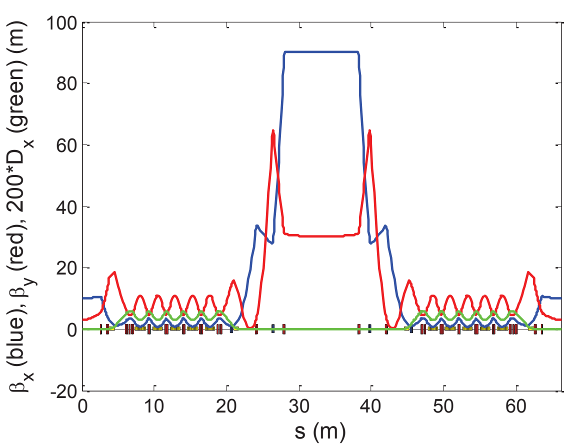

Figure 3: Layout and optical functions of two specially designed 7BAs with 10-m long straight section in between, for the latest version of the PEPX-type lattice for HEPS.

Table 1: Main Parameters of the Latest PEPX-type Lattice for HEPS

Parameters	**Values**	**Units**
Beam energy E_0	6(5)	GeV
Beam current I_0	200	mA
Bunch number n_B	2000	
Circumference C	1294.2	m
Horizontal damping partition number J_x	2.05	
Natural emittance ε_0	88 (61)	pm.rad
Working point (x/y/z)	93.14/49.4/0.006	
Natural chromaticity (x/y)	-112/-107	
Number of 7BAs	44	
Number of high-beta 10-m injection sections	2	
Beta functions in 10-m high-beta injection section (x/y)	90/30	m
Number of low-beta 5-m ID sections	42	
Beta functions in low-beta straight section (x/y)	10/3	m
RF voltage	10	MV
RF frequency	500.36	MHz
Harmonic number	2160	
Energy loss per turn	2.25	MeV
Damping times (x/y/z)	11.2/23/24.3	ms
Energy spread	0.001	
Natural bunch length	2.2	mm
Momentum compaction	5.9×10^{-5}	

NONLINEAR OPTIMIZATION

It is thought that the DA (in the injection plane) should be large enough (of the order of 10 mm) in the case of off-axis injection; and the MA should be large enough (~ 3%) for a long Touschek lifetime (e.g., for PEPX design [3], $T\sim 2.5$ h with $\delta_m = 2\%$, and ~ 21 h with $\delta_m = 3\%$).

In our study, we use a theoretical analyser [4] based on perturbation theory to derive the nonlinear terms [such as the detuning (up to the 2nd order), high-order chromatic (up to the 4th order), and resonance driving terms (up to the 6th order)] as polynomial functions of the sextupole and octupole strengths. With these polynomial functions one can quickly evaluate the nonlinear terms for different set of sextupole/octupole strengths, which makes it

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feasible to perform MOGA (multi-objective genetic algorithm [9]) optimization in a reasonable time (a few hours on a single PC). In this way, we can obtain the so-called Pareto optimal front that includes multi-solutions showing all the possible tradeoffs between the different objectives. The obtained results are then verified by calculating the DA and MA with numerical tracking and frequency map analysis [10].

With iterations of the above optimization routine, we find a solution (mode 1, see Fig. 4) promising large horizontal DA (larger than the physical aperture, 11 mm). However, for this mode, the MA is small with $\delta_m = 1\%$. This is because the analyser fails to predict the tune shifts with δ at relatively large momentum deviation. We then use directly the tune shifts with δ calculated numerically as the optimization goal, and search for the result promising a much less tune shift with δ and a moderate DA. In this way, we find solutions, mode 2 (see Fig.5) and mode 3 (see Fig. 6) with larger MA ($\delta_m = 1.8\%$ and 3%), with a price of smaller DA.

Further optimization is performed and it seems scarcely possible to obtain a mode with both large DA and large MA. As a compromise, one can use mode 1 during injection, and then switch to mode 2 and finally to mode 3 (it may take a few seconds) for a long enough Touschek lifetime. Since the linear optics remains the same for these three modes, and only sextupole/octupole magnets need to be ramped, it is believed that the dynamics will keep stable during the mode switching. Actually, this has been verified with numerical tracking, with the result shown in Fig. 7.

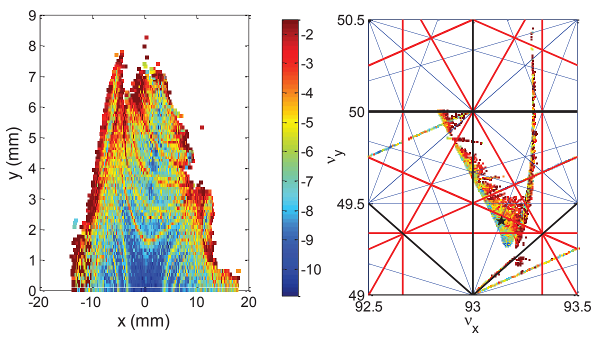

Figure 4: DA and FM for the latest version of the PEPX-type lattice for HEPS (mode 1).

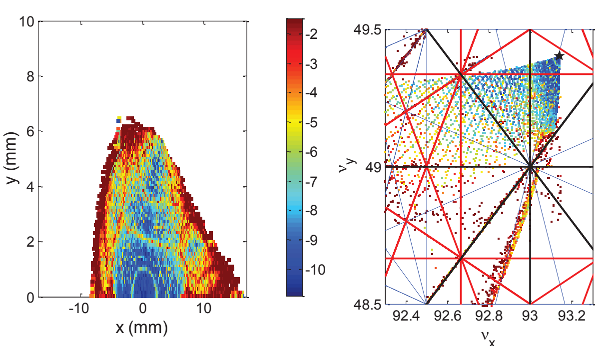

Figure 5: DA and FM for the latest version of the PEPX-type lattice for HEPS (mode 2).

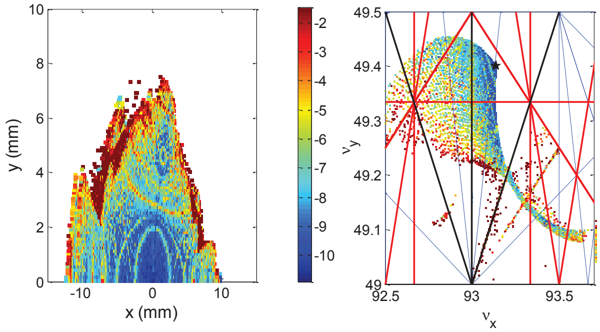

Figure 6: DA and FM for the latest version of the PEPX-type lattice for HEPS (mode 3). In this figure and also in Figs. 4 and 5, the colours, from blue to red, represent the stabilities of the particle motion, from stable to unstable.

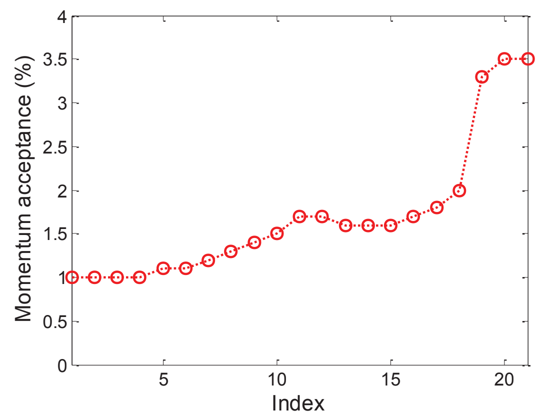

Figure 7: Simulation results of the MA variation during mode switching for the latest version of the PEPX-type lattice for HEPS, where index 1 represents mode 1, index 11 represents mode 2 and index 21 represents mode 3.

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