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STATUS OF HEPS LATTICE DESIGN AND PHYSICS STUDIES*

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Abstract

The High Energy Photon Source (HEPS) is a 6-GeV, kilometer-scale, ultralow-emittance storage ring light source to be built in Beijing, China. The HEPS is now under extensive design and study. In this report we will introduce the status of the HEPS lattice design and physics studies, including storage ring design, booster design, injection design, collective effects, error study, insertion device effects, longitudinal dynamics, etc.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, kilometer-scale, ultralow-emittance storage ring light source to be built in the Huairou District, northeast suburb of Beijing, and now is under extensive design.

As the R&D project for HEPS, the HEPS test facility (HEPS-TF) has started in 2016, and is to be completed by the end of Oct., 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, meanwhile, to complete the design for HEPS. One of the goals of the HEPS-TF project is to obtain an 'optimal' lattice design for the HEPS, study the related accelerator physics issues and ensure there is no show-stopper from beam dynamics point of view, and give as detailed parameter list and tolerance budget table as possible for various hardware systems.

This year, we start to prepare the conceptual design report and the feasibility study report of the HEPS project. After iterative discussions, the goal emittance of the HEPS storage ring lattice design is to obtain a natural emittance of below 100 pm.rad, and the ring circumference is fixed to 1360.4 m.

For the sake of the R&D of key hardware techniques and related physics issues, a hybrid-7BA lattice with a natural emittance of ~60 pm.rad and large ring acceptance that promises different candidate injection schemes was proposed (see below for details).

Based on this lattice, we carry out related physics studies for the HEPS, including collective effect study, error effect and lattice calibration simulation, injection system design, injector design, etc. In addition, we also continuously do optimizations to look for lattice with even better performance.

In the following we will briefly introduce the status of the lattice design, and recent progress of studies on the related physics issues.

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LATTICE DESIGN & PHYSICS STUIDES

Storage Ring Lattice Design

After various attempts of ultralow-emittance lattice designs and nonlinear optimizations [1-8], now the hybrid-7BA is chosen to be the basic layout of the HEPS storage ring. The optical function of one 7BA of the present lattice is shown in Fig. 1, and the main parameters of the ring are listed in Table 1.

After systematic optimization of both linear and nonlinear dynamics, as shown in Figs. 2 and 3, the 'effective' on-momentum dynamic aperture (DA) and momentum acceptance (MA) are 8 mm and 3.3 mm in *x* and *y* planes, and ~3.5%, respectively (see [9] for definition and discussion of the 'effective' DA and MA). The large ring acceptance makes it feasible to use on-axis swap-out, on-axis longitudinal accumulation, or even off-axis multipole injection method in the HEPS storage ring.

It is worth mentioning that there is a trade-off between the emittance (which is positively correlated to the available maximum brightness) and the ring acceptance. On the other hand, the choice of injection method is related to the available of the ring acceptance. Generally speaking, conventional local-bump injection method requires a DA of larger than 10 mm, off-axis injection with multipole requires a DA of at least 5 mm, on-axis longitudinal injection requires that both on-momentum and off-momentum DAs are 1 to 2 mm, on-axis swap injection only requires an on-momentum DA of 1 to 2 mm.

Actually, this lattice is selected among those obtained from the global optimization of the hybrid-7BA lattice, where the linear and nonlinear dynamics are simultaneously optimized and all the available tenable element parameters are scanned. The results are presented in Fig. 4. It shows that with the hybrid-7BA lattice, if satisfying only the DA requirement of on-axis swap-out injection, the HEPS ring emittance can be down to ~45 pm.rad; if pursuing large ring acceptance that allows for accumulation injections, the DA can be optimized to be close to (if not larger than) 10 mm in the injection plane, while keeping the emittance to be around 60 pm.rad.

Except the layout presented in Fig. 1, we are exploring and comparing different types of lattice structures and globally scanning all tuneable parameters of the ring with stochastic optimization methods, with the aim to achieve lattice with even better performance. This will be reported in a forthcoming paper.

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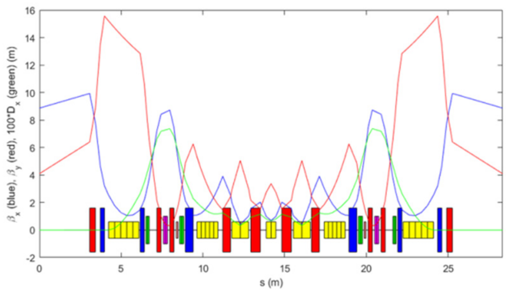

Figure 1: Optical functions and lattice layout of one 7BA of the present HEPS lattice.

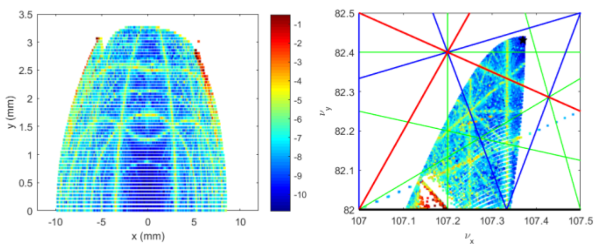

Figure 2: Effective (on-momentum) dynamic aperture and the corresponding frequency map of the present HEPS lattice.

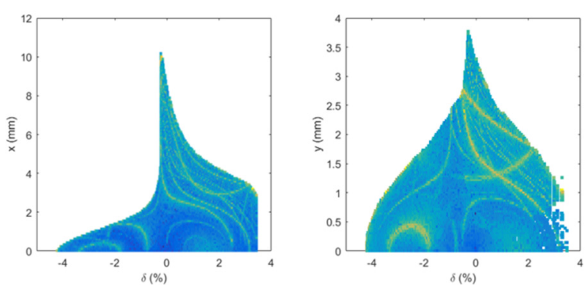

Figure 3: Effective momentum acceptance of the present HEPS lattice.

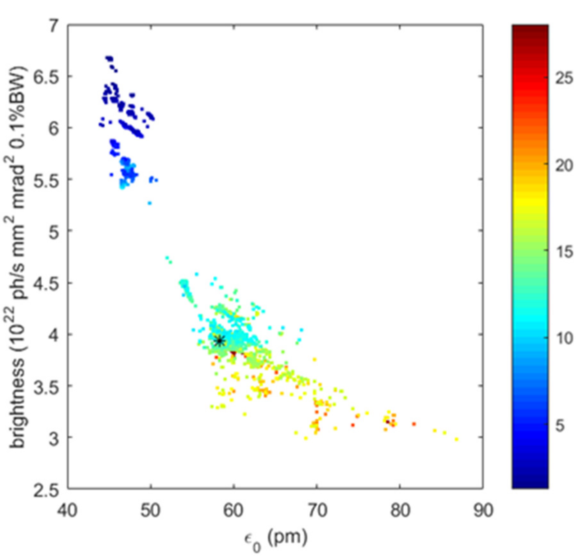

Figure 4: Solutions of global optimization of the hybrid-7BA lattice, the present lattice is represented with a black asterisk.

Table 1: Ring Parameters of Present HEPS Lattice

Parameters	Values
Energy E_0	6 GeV
Beam current I_0	200 mA
Circumference	1360.4 m
Natural emittance ε_{x0}	58.4 pm.rad
Working point υ_x/υ_y	107.37/82.43
Natural chromaticities (H/V)	-214/-133
No. of superperiods	48
ID section length L_{ID}	6.15 m
Beta functions at ID sect. (H/V)	8.9/4.1 m
Energy loss per turn	1.959 MeV
Rms energy spread	8.20×10^{-4}
Momentum compaction	3.43×10^{-5}

Injection to the Ring

The nominal injection scheme presently under consideration is the on-axis swap-out injection. The design also leaves space for other injection schemes, especially the on-axis longitudinal injection [e.g., 10]. Two operational modes with different filling patterns are considered, i.e., low-charge mode (200 mA with 680 bunches) and high-charge mode (200 mA with 63 bunches).

To inject a high-charge bunch to the ring, while avoiding the strong collective effects at the low energy of the booster ramping loop, a transport line from the storage ring to the booster (STB) has been designed [11] to allow for accumulation of the extracted bunches from the storage ring in the booster at 6 GeV. Especially for the high-charge mode, when the charge of the stored bunch of the ring reduces, this bunch will be extracted and injected to the booster after passing through the STB. The bunch will merge with existing bunch in the booster, and then be extracted from the booster and re-injected to the ring.

Error Study and Lattice Calibration

Associated with the compact layout and strong focusing of the ultralow-emittance design, the ring performance is sensitive to various errors, such as the alignment error, magnetic field error, BPM error, etc.

One critical concern is that whether we can smoothly and quickly store the beam in such an ultralow-emittance ring. To this end, we simulate the beam injection of the first several turns, and develop an automatic correction procedure to gradually reduce the amplitude of the particle oscillation and finally realize storage of the beam [12].

We evaluate the error effects by modelling these errors in the lattice and simulate the lattice calibration process, including orbit correction, optics correction and coupling control [13]. From this study we will also get detailed tolerance table for related hardware systems.

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Collective Effects

The fundamental frequency of the HEPS RF system is chosen to 166.6 MHz. To release the strong intrabeam scattering (IBS) and Touscheck effects related to the increasing beam density with the decreasing emittance, we adopt third-order harmonic RF cavities with frequency of 499.6 MHz. With the harmonic cavities, the bunch length can be lengthened by about 3 times so as to greatly release the IBS and Touschek effects. The Touschek lifetime is about 20 hours for the low-charge mode and 3 hours for the high-charge mode.

The impedance budget of the HEPS storage ring is estimated [14]. It is found that the main contributions to the longitudinal impedance are resistive wall impedance and elements with large quantity, and the transverse broadband impedance is dominated by the resistive wall impedance due to the small-aperture vacuum chamber.

Based on the impedance model, the collective effects are evaluated with both analytical analysis and numerical simulations, especially for the high-charge mode.

Among the single bunch instabilities, the transverse mode coupling instability is the strongest one. It leads to a threshold current of ~ 0.1 mA at zero chromaticity. This problem, however, can be resolved with a positive chromaticity, e.g., +2. Actually, in HEPS design, we set the corrected chromaticities to (+5, +5).

For the coupled bunch instabilities, the main contributors are the high-order modes of RF cavities and the resistive wall impedance (the full aperture of the vacuum chamber is on the level of 25 mm). To cure the instabilities and ensure stable operation, feedback system with damping time of shorter than 0.5 ms is required.

Injector Design

The booster will accelerate the beam from 300 MeV to 6 GeV, and is assumed to be located in a separate tunnel, so as to reduce the effect of the ramping cycle of the booster to the particle motions of the ring.

To fulfil the requirements for the expected light source performance, it is required that the booster should have the ability to provide high enough charge bunch, i.e., 15 nC. Study shows that the single bunch instability causes stringent limitation to available stored bunch charge at the low energy.

Efforts are made to release this limitation as much as possible. The lattice is changed from a 15BA layout to a FODO structure. The latter one allows larger momentum compaction factor, which is helpful to increase the bunch charge threshold. In addition, the average beta function of the lattice is reduced. And, it is required that the electron bunch from the linac should have a long bunch length, i.e., not less than 25 ps or namely 7.5 mm. Even with these measures, the bunch charge threshold cannot be increased to be above 15 nC. As mentioned above, it is determined to build an additional transport line between ring and booster to overcome this problem.

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