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PROGRESS OF LATTICE DESIGN AND PHYSICS STUDIES ON THE HIGH ENERGY PHOTON SOURCE*

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Abstract

The High Energy Photon Source (HEPS) is an ultralow-emittance, kilometer-scale storage ring light source to be built in China. In this paper we will introduce the progress of the physical design and studies on HEPS over the past one year, covering issues of storage lattice design and optimization, booster design, injection design, collective effects, error study, insertion device effects, beam lifetime, etc.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, 1.3-km, ultralow-emittance storage ring light source to be built in the Huairou District, northeast suburb of Beijing, China.

As the R&D project for HEPS, the HEPS test facility (HEPS-TF) has started in 2016, and is to be completed in Oct., 2018. The goals of the HEPS-TF project are to develop key hardware techniques that are essentially required for constructing a diffraction-limited storage ring light source and complete the design for the HEPS project.

For the sake of the R&D of key hardware techniques and studies of the related physics issues of the HEPS-TF project, a baseline lattice consisting of 48 identical hybrid-7BAs (first used in ESRF-EBS [1]) was proposed, with a natural emittance of about 60 pm [2]. Continuous optimization of this lattice was performed to explore its ultimate performance [3-8]. In 2017, a 58-pm lattice with basically the same layout but a larger dynamic aperture (of the bare lattice) was proposed [9], based on which related physics studies were carried out to identify the challenging issues that may affect the overall performance of the light source, look for corresponding solutions and demonstrate the effectiveness of novel methods proposed for the HEPS.

Soon afterwards, a new hybrid 7BA lattice with super-bends and anti-bends was proposed for the HEPS [10], promising a lower natural emittance, i.e., 34 pm, and a higher brightness. Now we are carrying out extensive physics studies based on this lattice, including collective effect study, error effect and lattice calibration simulation, injection system design, injector design, hoping to reach a complete design of the HEPS project in a few months.

In the following, we will briefly introduce the progress of the lattice design and related physics studies based on the 58-pm and 34-pm lattices over the past one year.

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LATTICE DESIGN & PHYSICS STUDIES

Storage Ring Lattice Design

The preliminary lattice design studies of the light source (called Beijing Advanced Photon Source that time) were launched in 2008. To date the HEPS design has been evolved for about ten years [11].

In 2017, global optimization of the HEPS lattice with 48 identical hybrid-7BAs were performed, where the all tuneable element parameters were used as variable, and the brightness instead of natural emittance [12] and the 'effective' DA and MA (considering the limitation of integer and half integer resonances [13]) were used as optimizing objectives. A successive and iterative application of PSO and MOGA algorithms was adopted to avoid solutions being trapped in local optima during evolution [7]. In the optimization we first kept the "$-I$ transportation" condition by varying the strengths of three families of quadrupoles, and then removed this constraint (this allows three more knobs), which brought us solutions with optics that does not meet the '$-I$ transportation' condition [14]. The lowest possible natural emittance is about 45 pm. Nevertheless, among these solutions, a 58-pm lattice, with a large effective DA (above 8 mm in x plane, larger than 300 times of rms equilibrium beam size) and MA (larger than 3%) of the bare lattice were chosen as the baseline for the feasibility study report of the HEPS project. The layout and optical functions of one 7BA are shown in Fig. 1.

Meanwhile, we also tried to explore even better lattice structures. A comparison of several ultralow-emittance unit cells [15] indicated that the modified-TME unit cell with antibend and longitudinal gradient dipole (also called superbend here) allows the lowest possible emittance, given a long enough cell length. It was then proposed to replace the middle unit cell of a hybrid-7BA with such a unit cell to reach an even lower natural emittance. In addition, based on the investigation of the user requirements on radiation quality, we divided the 48 hybrid 7BAs into 24 periods, with alternating high- and low- beta sections. In this way, one can further push down the beta functions to those values that results in the highest possible brightness in one ID section, and match the beta functions of another section to moderate values to achieve an adequate dynamic aperture for the on-axis injection. The above considerations together brought about the latest 34-pm HEPS lattice, with the layout and optical functions of one period (two 7BAs) shown in Fig. 2. The DA of the bare lattice is about 6 mm and 4 mm in x and y planes (not shown here due to limited space). The effective momentum acceptance is about 3%.

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One important property of this design is that it provides a flexible source for dipole beam lines. The central slice of the superbend having the highest peak field was used for bending magnet beam lines. It is not necessary to use additional dipole radiators, e.g., three-pole wigglers. Study shows that once the total bending angle and the dipole length of this dipole are kept the same, one can vary the field of the central slice to provide X-rays with different critical photon energy, while causing little perturbation to the ring optics and nonlinear performance.

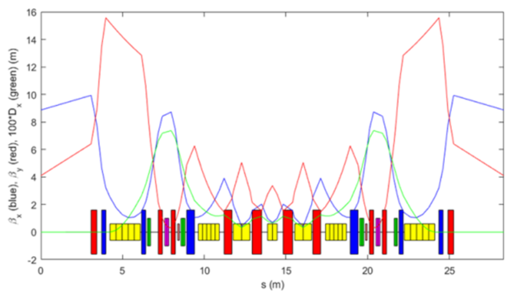

Figure 1: Optical functions and layout of one 7BA of the 58-pm lattice.

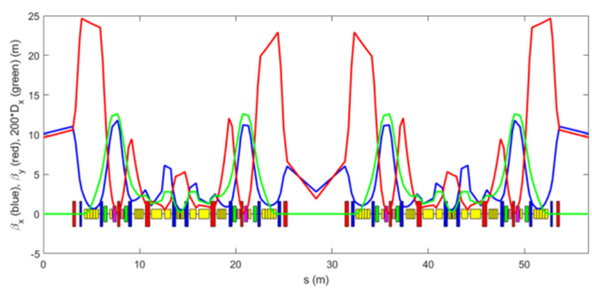

Figure 2: Optical functions and layout of one period (two 7BAs) of the 34-pm lattice.

Injection Design

We consider the on-axis swap-out injection as the baseline injection scheme, while reserving possibilities for other injection schemes, in particular the on-axis longitudinal injection schemes (e.g., [16, 17]). The swap-out injection greatly relaxes the requirements on dynamic aperture compared with conventional off-axis injection schemes. The main challenge is that the booster should provide bunches with high enough charge. For the high-bunch-charge mode (200 mA, 63 bunches), a 14.4-nC bunch is required.

We proposed a 'high-energy accumulation' scheme [18] where the booster is also used as a full energy accumulator ring. Taking the high-charge mode as an example, when the charge of one bunch in the ring reduces by a certain factor (e.g., from 14.4 nC to 13 nC), this bunch will be extracted and injected to the booster after passing through the transport line from the ring to the booster. The bunch will merge with an existing bunch in the booster (e.g., 1.4 nC) which has been injected from the linac and accelerated to 6 GeV. And then the merged bunch (in this example, now the charge is recovered to 14.4 nC) is extracted from the booster and re-injected to the ring.

This scheme is more economical compared to using a dedicated full energy accumulator ring, and helps to avoid challenges associated with the acceleration of high charge bunches in the booster and a careful beam dump design in the storage ring. However, this scheme requires an additional transport line from the storage ring to the booster, and it is essential to maintain a high enough transfer efficiency throughout the whole injection process, so that the beam charge loss can be compensated by the accelerated small charge bunches, to ensure successful top-up operation. We are carrying out detailed studies with the aim to clarify the error tolerances for the elements of the injection, extraction systems as well as the transport lines.

Injector Design

The HEPS injector consists of a linac and a booster, which are located in separate tunnels from that of the storage ring. This arrangement is expected to effectively reduce the impact of the booster ramping on the beam dynamics of the storage ring.

The linac employs normal conducting S-band bunching and accelerating structures. It delivers electron bunches with energy of 500 MeV and normalized emttiance of 40 µm. These beams are transferred to the booster via a transport line.

The booster originally utilized a 15BA lattice to gain an emittance as low as 4 nm [19]. However, this lattice has a very small momentum compaction factor, limiting the maximum bunch charge at the injection energy due to collective effects. Then, a FODO lattice was adopted. This lattice allows a larger momentum compaction factor, which significantly increases the bunch charge threshold at the injection energy. As a price, the natural emittance of the booster at 6 GeV is increased from 4 nm to 40 nm, which still satisfies the demand of the storage ring injection. More details of the injector can be found in [20].

Insertion Devices

Parameters of insertion devices (IDs) were designed for the 14 beam lines to be constructed in the first phase of the HEPS project and are under optimization. In the present design, there are 7 beam lines based on the in-vacuum insertion device while the others are based on the insertion devices in air.

Dynamic effects of IDs on storage ring were investigated. It was found that the IDs can cause a vertical tune shift of totally 0.03 and a vertical beta beating of 0.3%. This, however, can be corrected by the nearby quadrupoles. Two correctors with the maximum strength of 400 µrad near each ID with two feed-forward coils are introduced to adjust the close orbit distortion cause by the ID integral field errors. The additional electron energy loss per turn caused by IDs is 1.5 MeV. Horizontal emittance can be reduced to 27.5pm when the IDs are included in the 34-pm lattice.

Error Study and Lattice Calibration

In the presence of typical alignment, magnetic field, ID, and BPM errors, simulations indicate that it is very difficult

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to accumulate the beam in the storage ring. To deal with this problem, we developed an automatic correction procedure that can gradually reduce the amplitude of the particle oscillation and finally realize storage of the beam [21]. Recent simulation indicated that the accumulation rate can be above 90% with practical errors in the ring and upper limit of the corrector strength of 0.4 mrad.

We have simulated the lattice calibration process with the AT program. For the HEPS lattice, by looking inside the error sources, we found the nonzero offset in sextupoles provides more than 90% quadrupole field error and is main contributors of DA reduction [22]. Thus, we included the sextupole alignment based on beam response in the lattice calibration simulation [23], which provides better correction ability and helps to recover the nonlinear performance. The beta beating after correction is smaller than 0.5%. And DA is larger than 2 mm in vertical plane and 3 mm in horizontal plane, which is able to meet the injection requirements.

Collective Effects

The fundamental frequency of the HEPS RF system is chosen to be 166.6 MHz. Third-order harmonic RF cavities are used for bunch lengthening.

The impedance budget of the HEPS storage ring was updated. Based on the latest impedance model, the collective beam instabilities have been evaluated by both analytic formulae and multi-particle tracking simulations [24, 25].

The simulations show that the microwave instability threshold increases from about 0.9 nC to about 2.2 nC because of the use of the harmonic cavity.

For the transverse mode coupling instability, the threshold is only about 0.4 nC per bunch at zero chromaticity, which is far below the required single-bunch charge. However, this problem can be solved by implementing positive chromaticity. In HEPS storage ring design, the corrected chromaticities can be up to (+5, +5). Simulations show that the threshold of transverse single-bunch instabilities is higher than 30 nC when the chromaticities are set to (+5, +5).

For the coupled bunch instabilities, the main contributors are the high-order modes (HOMs) of the RF cavities and the transverse resistive wall impedance. In the storage ring, HOM damper has been carefully designed and optimized to damp the HOMs of the superconducting cavities. Longitudinal and transverse feedback systems are needed to damp the instabilities. Detailed simulation studies with feedback are underway.

Lifetime Study

For the latest lattice, assuming the coupling factor is 10%, the Touschek lifetime was evaluated based on the local momentum acceptance (see Fig. 3) after the simulation of error effects and lattice calibration [22].The beam parameters used for lifetime evaluation for the high-brightness mode (200 mA, 680 bunches) and high-bunch-charge mode were calculated and listed in Table 1, considering the effects of harmonic cavity, impedance and intrabeam scattering effect. The tenth-percentile lowest Touschek lifetime is 4.0 hours for high-brightness mode and 0.87 hours for high-bunch-charge mode. Slightly longer lifetime can probably be achieved in the actual machine. The residual gas scattering lifetime was also calculated, under the assumptions that the pressure in the vacuum chamber is 1 nTorr (with 80% H_2 and 20% CO) and the residual gas temperature is 293.15K. The lifetime due to elastic scattering is 130 hours and that due to inelastic scattering is 257 hours.

Table 1: Beam Parameter for Touschek Lifetime Evaluation

Parameter	High-Brightness	High-Bunch-Charge
ε_x [pm]	27.5	33.0
σ_δ [10^{-3}]	1.11	1.93
σ_z [mm]	32.0	48.0

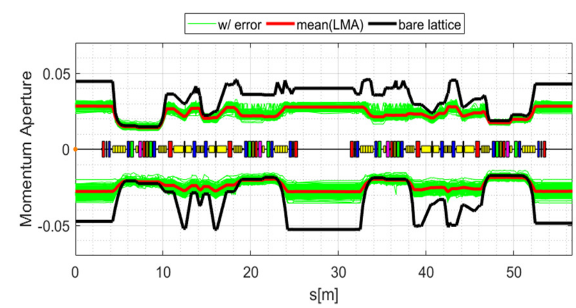

Figure 3: Local momentum aperture along one period of the HEPS, considering error effects (200 seeds).

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