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

Y. Jiao†, X.H. Cui, Z. Duan, Y.Y. Guo, P. He, X.Y. Huang, D.H. Ji, H.F. Ji, C. Li, J.Y. Li, X.Y. Li, C. Meng, Y.M. Peng, Q. Qin, S.K. Tian, J.Q. Wang, N. Wang, Y.Y. Wei, G. Xu, H.S. Xu, F. Yan, C.H. Yu, Y.L. Zhao, Key Laboratory of Particle Acceleration Physics and Technology, IHEP, CAS, Bei-jing, China

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 physics design and related studies of HEPS over the past year, covering issues in storage ring lattice design, injection and injector design, insertion device effects, error study and lattice calibration, collective effects, 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 Beijing, China.

The HEPS Test Facility (HEPS-TF [1]), as the R&D project for HEPS, was started in 2016 and completed in 2018. A series of key technologies for the accelerator and the beamlines required for constructing a diffraction-limited storage ring light source have been demonstrated, including high-gradient (80 T/m) quadrupoles, nanosecond-level pulsed kicker, small-aperture NEG-coated vacuum system, high energy and high resolution monochromator, time-resolved X-ray techniques, pixel array detectors, etc.

As one of the most important tasks of the HEPS-TF, a baseline lattice, with a natural emittance of 34.2 pm, was proposed for the HEPS storage ring. Based on this lattice, studies were carried out to ensure that there was no show-stopper from beam dynamics point of view. At the end of 2018, the preliminary design report of the HEPS was finished.

Currently, the HEPS team focuses mainly on the engineering design. The first version of parameter list and the tolerance budget for the hardware systems have been released. To address the challenges and problems emerging in the technical design, necessary iterative design modifications among beam physics group and engineering groups are underway.

LATTICE DESIGN & PHYSICS STUIDES

Storage Ring Lattice Design

The lattice design of the HEPS storage ring was started from around ten years ago [2]. The very first lattice was in a DBA structure, with 48 DBAs and a beam emittance of 1500 pm [3]. Thereafter different lattice structures were explored, such as standard 7BA [4], TBA [5], standard 7BA with high-gradient quadrupoles [6], hybrid 7BA with high-gradient quadrupoles [7-10], and modified hybrid 7BA including super-bends and anti-bends [11-13].

The baseline lattice of the storage ring was fixed at around March 2018 (referred to as V2.0 lattice), which consists of 48 modified hybrid 7BAs, and results in a natural emittance of 34.2 pm [13]. Different from a standard hybrid 7BA lattice, two families of anti-bends are used to achieve as low emittance as possible. A dipole combined with longitudinal gradient instead of transverse gradient is adopted in the middle of each 7BA, with its central slice as the source of bending magnet beam line. In addition, alternating high- and low-beta straight sections are implemented into the optics design, in order to maximize the brightness in half of the 6-m straight sections, by reducing both horizontal and vertical beta functions at the center of straight sections down to about 2 m.

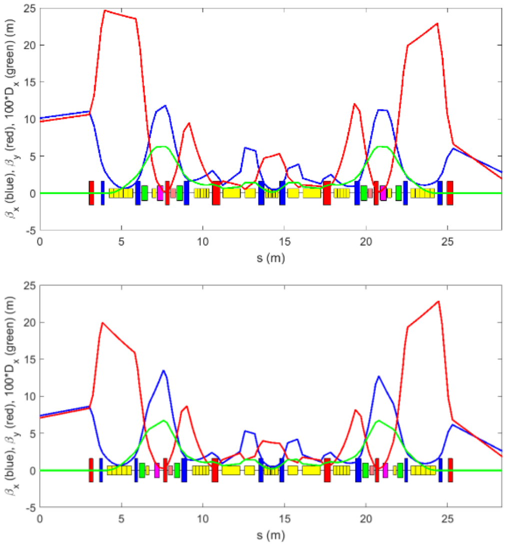

Figure 1: Optical functions and layout of one 7BA of the HEPS storage lattice, V2.0 (upper) and V2.4α (below).

During the engineering design, a few modifications to the lattice were made. The upper limit of all quadrupole gradients were set to about 80 T/m, the magnetic fields of the middle three dipoles in each 7BA were reduced, and the distance between adjacent magnets were enlarged to resever enough space for hardware components. The emittance remains almost the same, while the dynamic aperture becomes slightly smaller. The new lattice is referred to as V2.4α lattice. The optics and layout of one

---

* Work supported by NSFC (11475202, 11405187, 11205171)
† jiaoyi@ihep.ac.cn

7BA of V2.0 and V2.4α lattice are shown in Fig. 1. Further optimization is under way.

Injection Design

On-axis swap injection has been chosen as the baseline injection scheme for HEPS storage ring. In particular, to address the great challenges in delivery of 14.4 nC full charge bunches to the storage ring for timing experiments, it was proposed to use the booster as a full energy accumulator, to recycle and replenish the used bunch in the storage ring [14].

This scheme relieves the potential beam instability issues at the booster injection energy, while high transmission efficiency is mandatory for the injection of both storage ring and booster. Analysis of the injection errors and injection efficiency simulations based on the V2.0 design was done [15]. On the other hand, there are some transient beam instabilities during injection into the storage ring, which could lead to some beam loss for a 14.4 nC injected bunch. Preliminary simulations [16] point out several possible measures to relieve the beam loss. Further investigation is under way.

Injector Design

The injector is composed of a 500-MeV Linac, a 6-GeV booster and three transport lines. The layout of the injector is shown in Fig. 2.

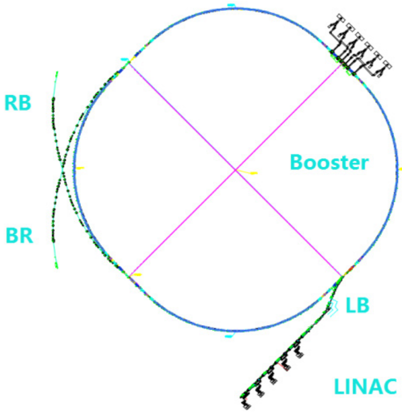

Figure 2: Layout of the HEPS injector.

According to the latest requirement for the injector, the linac should be able to provide electron beam with a bunch charge higher than 7 nC to the booster. A new bunching system has been designed [17], which is composed of two sub-harmonic bunchers, a S-band buncher and a standard accelerating structure. The frequency of the Linac signal generator is 499.8 MHz, the frequencies of two sub-harmonic buncheres are chosen as 166.6 MHz and 499.8 MHz. The electron gun can provide 10 nC electron bunches and the Linac can provide about 8.5 nC electron bunches, with beam energy of 500 MeV and normalized emittance of 50 mm-mrad at the exit of the Linac.

The HEPS booster adopts a four-fold symmetric FODO lattice with single-function magnets. Each fold consists of 14 standard FODO cells and 2 matching cells [18]. In the past year, several changes were made. To fit the timing requirements of the injection scheme, the circumference of the booster was adjusted to 454 m. Concrete layout of the magnets and other devices were studied. Since the V2.4α ring lattice has a smaller acceptance, the booster lattice is optimized with a combination of MOGA and PSO [10] to ensure high enough injection efficiency. It appears feasible to reduce the natural emittance of the booster at 6 GeV to about 16 nm. Further optimization is under way.

Insertion Device Effects

In phase I of the HEPS project, it is planned to build 14 user beamlines and one test beamline. Different types of insertion devices, such as CPMU, in-vacuum and in-air undulators, APPLE-Knot undulator and wiggler, are considered to satisfy diverse requirements from users.

A Taylor expanded generating function of the undulator magnetic field [19] has been developed and applied in Accelerator Toolbox to create a second-order symplectic integrator routine for particle tracking and beam dynamics studies [20].

Recently, it was found that the impact of APPLE-Knot undulator on the dynamic aperture is non-ignorable, especially when it is operated in vertical polarization mode. Further studies on the APPLE-KNOT undulator are underway.

Error Studies and Lattice Calibration

Simulations have been performed to study the error effects, lattice calibration [21] and first-turn around [22]. Current studies concentrate on commissioning process in realistic machine conditions. In the first-turn around process, the sextupoles and octupoles are turned off. An injected beam can circulate a few thousand turns, but cannot be stored. Therefore, a fast optics correction using the turn-by-turn BPM data is required, in order to reduce the optics distortion and ensure a stored beam. Preliminary simulation results are presented in [23].

Collective Effects

A comparatively complete impedance model had been obtained including various major vacuum components of the HEPS storage ring [24-26]. Based on the impedance model, we have carried out systematic studies of the collective effects, such as impedance driven instabilities, beam lifetime, ion effects, and intra-beam scattering [27-32].

In the past year, the dominant impedance contributors, such as the bellows, RF-sealed flanges, strip-line kickers, in-line absorbers etc. have been optimized.

For the coupled-bunch instabilities, calculations indicate that there are two dangerous HOMs from the RF cavities. Detailed design of the HOMs damping scheme is still on-going by the RF colleagues to suppress these two modes.

As to the collective effect due to beam-ion interaction, a “strong-strong” simulation code is under development to study various scenarios in the near future.

The intra-beam scattering effect was studied with a more realistic model including the effects of IDs, beam lengthening with harmonic cavity and impedance. No apparent emittance degradation due to IBS is observed.

In addition, we carried out careful studies of the impedance and collective instabilities for the HEPS booster [33, 34]. A preliminary impedance model was obtained, and used in the study of both longitudinal and transverse single-bunch instabilities. Furthermore, the energy ramping process has been included in the study of collective instabilities in the booster [35].The transverse single-bunch instability significantly influences the booster lattice design and injection design. Iterative evolution of booster design, with the evaluation of instabilities, is under way.

Collimator Design

Collimator simulations for Touschek scattered particles were performed based on V2.0 lattice. It was found that more than 70% particle losses took place in the first turn if no collimator was implemented (see Fig. 3). This was due to the fact that the vertical betatron tune in one superperiod is very close to half integer for a momentum deviation of 4%. While the new lattice, V2.4α, does not have such problem (see Fig. 4). Simulations based on V2.4α lattice show that about 80% of particle losses occur after multiple turns. More detailed collimator simulation studies are underway.

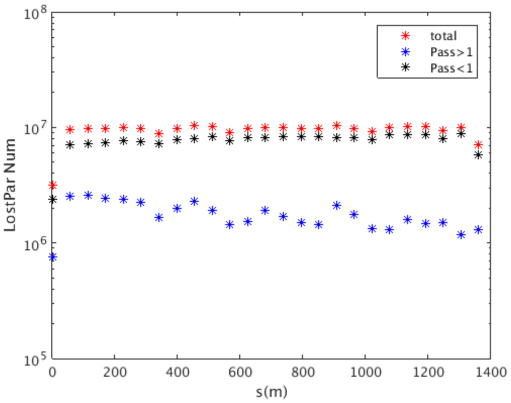

Figure 3: Statistics of the Particle loss due to Touschek scattering based on V2.0 lattice. More than 70% particle losses occur in the first turn.

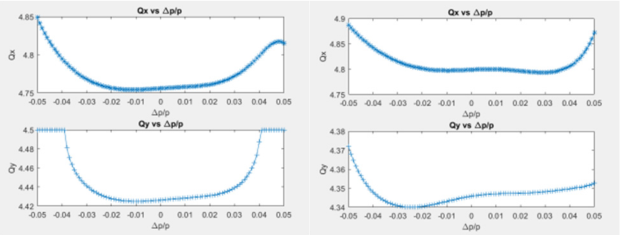

Figure 4: Variation of the betatron tunes of a superperiod with respect to the momentum deviation, for the V2.0 (left) and V2.4α (right) lattices.

Ground Motion Studies

The slab design is required to control the tunnel ground vibration below 25 nm (RMS displacement integral over 1 Hz up to 100 Hz). Two prototype slabs were constructed in HEPS site. The first scheme is constructed with 1-m reinforced concrete slab and 1-m replacement layer using graded sand and stone. The second scheme is the same as the first one but with 5-m grouted layer under the graded sand and stone. Measurements show that for both schemes, the ground motion level (RMS displacement integral over 1-100 Hz) is smaller than green field. However, when using vibration exciter for vibration response measurement of first scheme for all frequency range of interest, the results shows that vibration level is amplified for certain frequency range, as shown in Fig. 5. The reason is still under investigation.

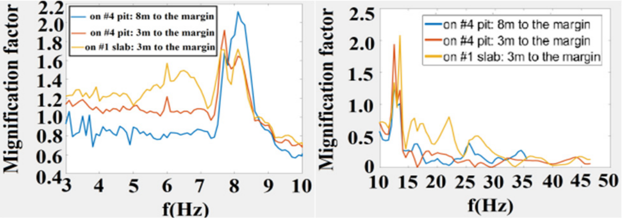

Figure 5: Amplification of vibration for the first scheme, from 1 to 100 Hz.

Beam Orbit Stability

The beam orbit stability requires the rms position and angular motion of the electron beam less than 10% of the beam size and divergence in transverse planes for the insertion devices and vertical plane for bending magnet sources, corresponding to orbit fluctuations tolerance of 1 μm in horizontal and 0.3 μm in vertical plane, respectively. In order to eliminate the fast fluctuation of the beam orbit, a global FOFB system was proposed [36] with an effective bandwidth up to 1000 Hz, and with sampling rate and correction frequency of about 20 kHz. Simulation of the beam dynamics with FOFB is under way.

Apart from the ground motions, another important contributor to time dependent orbit fluctuations, electric power noise, was investigated. For simplicity, in the simulation, an orbit distortion reduction factor of 1/4~1/3 from the feedback system was assumed, and ground vibrations with amplitude of 25 nm rms were considered. Results indicated that the power supply ripple of the storage ring should be below 10 ppm.

SUMMARY

In the past one year, the HEPS physics design was continuously evolved, in order to provide as a solid basis as possible to the construction of this project that will be started soon in this year.

REFERENCES

[1] X.M. Jiang, J.Q. Wang, Q. Qin *et al.*, "Chinese high energy photon source and the test facility" (in Chinese). Sci Sin-Phys Mech Astron, 2014, 44: 0175-1094.

[2] Y. Jiao *et al.*, “Evolution of the lattice design for the High Energy Photon Source”, in Proc. IPAC’18, TUPMF049, Vancouver, Canada, 2018.4.

[3] X. Jiang *et al.*, “BAPS Preliminary Design Report”, internal report, 2012.

[4] G. Xu and Y. Jiao, “Towards the ultimate storage ring: the lattice design for Beijing Advanced Photon Source”, *Chin. Phys. C*, 37(5), 057003 (2013).

[5] G. Xu and Y.M. Peng, “Minimum emittance in TBA and MBA lattices”, *Chin. Phys. C*, 39(3), 037005, 2015.

[6] Y. Jiao and G. Xu, “PEPX-type lattice design and optimization for the High Energy Photon Source”, *Chin. Phys. C*, 39(6), 067004, 2015.

[7] G. Xu, Y. Jiao, Y. Peng, “ESRF-type lattice design and optimization for the High Energy Photon Source”, *Chin. Phys. C*, 40(2), 027001, 2016.

[8] Y. Jiao, “Improving nonlinear performance of the HEPS baseline design with a genetic algorithm”, *Chin. Phys. C*, 40(7), 077002, 2016.

[9] Y. Jiao and G. Xu, “Exploring the ultimate linear and nonlinear performance of the HEPS hybrid 7BA design”, in *Proc. IPAC’16*, WEPOW025, Busan, Korea, 2016.5.

[10] Y. Jiao and G. Xu, “Optimizing the lattice design of a diffraction-limited storage ring with a rational combination of particle swarm and genetic algorithms”, *Chin. Phys. C*, 41(2), 027001, 2017.

[11] Y. Jiao *et al.*, “Accelerator Physics studies for the High Energy Photon Source in Beijing”, in *Proc. FLS2018*, MOP2WB01, Shanghai, China, 2018.3.

[12] Y. Jiao, X.Y. Li, G. Xu, “Performance Comparison of Different Ultralow Emittance Unit Cells”, *J. Phys.: Conf. Ser.*1067, 032004, 2018.

[13] Y. Jiao, G. Xu, X. Cui, Z. Duan, Y.Y. Guo, P. He, D. Ji, J.Y. Li, X.Y. Li, C. Meng, Y.M. Peng, S.K. Tian, J.Q. Wang, N. Wang, Y.Y. Wei, H.S. Xu, F. Yan, C.H. Yu, Y.L. Zhao, Q. Qin*, “The HEPS project”, *J. Synchrotron Rad.* 25, 1611-1618, 2018.

[14] Z. Duan *et al.*, “The Swap-Out Injection Scheme for the High Energy Photon Source”, in *Proc. IPAC’18*, THPMF052, Vancouver, Canada, 2018.4.

[15] Z. Duan *et al.*, “Simulation of the Injection Efficiency for the High Energy Photon Source”, presented at IPAC’19, Melbourne, Australia, May 2019, paper TUPGW048, this conference.

[16] Z. Duan *et al.*, “Simulation of the injection transient instability for the High Energy Photon Source”, presented at IPAC’19, Melbourne, Australia, May 2019, paper TUPGW053, this conference.

[17] C. Meng *et al.*, “The Progress in Physics Design of HEPS Linac”, presented at IPAC’19, Melbourne, Australia, May 2019, paper MOPGW052, this conference.

[18] Y.M.Peng *et al.*, “Status of HEPS booster lattice design and physics studies”, in *Proc. IPAC’18*, TUPMF062, Vancouver, Canada, 2018.4.

[19] J. Bahrdt and G. Wüstefeld, “Symplectic tracking and compensation of dynamic field integrals in complex undulator structures”, *Phys. Rev. ST Accel. Beams*, **14**, 040703, 2011.

[20] X.Y. Li, *et al.*, “Effects of insertion devices on stored electron beam of High Energy Photon Source”, in *Proc. IPAC’17*, MOPVA026, Copenhagen, Denmark, 2017.5.

[21] D. Ji *et al.*, “Beam Performance Simulation with Error Effects and Correction on HEPS Design”, in *Proc. IPAC’18*, THPMF054, Vancouver, Canada, 2018.4.

[22] Y.L. Zhao *et al.*, “First turns around strategy for HEPS”, in *Proc. IPAC’17*, MOPIK082, Copenhagen, Denmark, 2017.5.

[23] D. Ji *et al.*, “Simulation of Model Independent Analysis to HEPS Storage RING”, presented at IPAC’19, Melbourne, Australia, May 2019, paper TUPGW043, this conference.

[24] N. Wang *et al.*, “Development of the impedance model in HEPS”, in *Proc. IPAC’17*, WEPIK078, Copenhagen, Denmark, 2017.5.

[25] N. Wang *et al.*, “Impedance and heat load analysis of the strip-line kicker in HEPS”, in *Proc. IPAC’18*, THPAK015, Vancouver, Canada, 2018.4.

[26] S.K. Tian *et al.*, "Longitudinal impedance measurement of the strip-line kicker for High Energy Photon Source (HEPS)", in *Proc. IPAC’18*, TUPMF053, Vancouver, Canada, 2018.4.

[27] N. Wang *et al.*, “Studies on collective instabilities in HEPS”, in *Proc. IPAC’17*, THPAB030, Copenhagen, Denmark, 2017.5.

[28] Z. Duan *et al.*, “Simulation of the single bunch instability for the high energy photon source”, in *Proc. IPAC’17*, THPAB029, Copenhagen, Denmark, 2017.5.

[29] N. Wang *et al.*, “Analytical estimation of the beam ion instability in HEPS”, in *Proc. IPAC’18*, THPAK014, Vancouver, Canada, 2018.4.

[30] S.K. Tian *et al.*, “Ion instability simulation in the HEPS Storage ring”, in *Proc. IPAC’18*, THPMF055, Vancouver, Canada, 2018.4.

[31] S.K. Tian *et al.*, “Ion instability in the HEPS storage ring”, in *Proc. FLS2018*, TUA2WB04, Shanghai, China, 2018.3.

[32] H.S. Xu *et al.*, “Influences of harmonic cavities on the single-bunch instabilities in electron storage rings”, in *Proc. FLS2018*, WEP2PT024, Shanghai, China, 2018.3.

[33] H.S. Xu *et al.*, “The influence of chromaticity on transverse single-bunch instability in the Booster of HEPS”, in *Proc. IPAC’18*, THPAF012, Vancouver, Canada, 2018.4.

[34] H.S. Xu *et al.*, “Studies of the single-bunch instabilities in the Booster of HEPS”, in *Proc. IPAC’18*, THPAF014, Vancouver, Canada, 2018.4.

[35] H.S. Xu *et al.*, “The Study of Single-Bunch Instabilities in the Ramping Process in the HEPS Booster”, presented at IPAC’19, Melbourne, Australia, May 2019, paper MOPGW052, this conference.

[36] D. P. Jin, “Preliminary Design and Performance Analysis of the FOFB System of HEPS”, reported in *GM’17*, Beijing, China, 2017.