60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources FLS2018, Shanghai, China JACoW Publishing
ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP2WB01

ACCELERATOR PHYSICS STUDIES FOR THE HIGH ENERGY PHOTON SOURCE IN BEIJING*

Y. Jiao†, X.H. Cui, Z. Duan, Y.Y. Guo, D.H. Ji, J.Y. Li, X.Y. Li, 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, Beijing 100049, China

Abstract

The High Energy Photon Source (HEPS) is the next ring-based light source to be built in China, with an emittance of tens of picometers, and a circumference of about 1.3 km. After 10 years' evolution, the design for the HEPS is recently basically determined. In this report we will briefly introduce the latest HEPS lattice design and the progress in related physics studies.

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. After iterative discussions, the goal emittance of the HEPS storage ring lattice design is to obtain a natural emittance of below 100 pm.rad.

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 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 meanwhile, to complete the design for the HEPS project. The main goal of accelerator physics studies is to obtain an 'optimal' lattice design for the HEPS, study the related 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.

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 with 48 identical hybrid-7BAs, a natural emittance of about 60 pm and a large ring acceptance that promises different injection schemes was proposed [1].

For the HEPS project, in 2017, we finished the conceptual design report and the feasibility study report. Now we are preparing the preliminary design report, hoping that we could start the construction before 2019.

Recently, a new lattice with a lower natural emittance, i.e., 34 pm, was proposed for the HEPS project, which still consists of 48 hybrid-7BAs but in 24 periods, and contains superbends and anti-bends.

Based on this lattice, we are carrying out related physics studies, including collective effect study, error effect and lattice calibration simulation, injection system design, injector design, etc. In the following, we will briefly overview the evolution of the lattice design and introduce the status of the related physics studies.

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

LATTICE DESIGN & PHYSICS STUIDES

Early in 2008, a kilometre-scale storage ring light source with beam energy of 5 to 6 GeV was proposed to be built in Beijing [2] (called Beijing Advance Photon Source that time). Extensive efforts have been made on the lattice design and related physics studies. As shown in Fig. 1, over the past ten years, the lattice structure has been continuously evolved, from DBA, standard 7BA, TBA, standard 7BA with high-gradient quadrupoles, hybrid 7BA with high-gradient quadrupoles [3-15], to the latest structure, hybrid 7BA with super-bends and anti-bends. The beam energy was fixed to 6 GeV around 2014. The circumference was fixed to 1360.4 m in 2017.

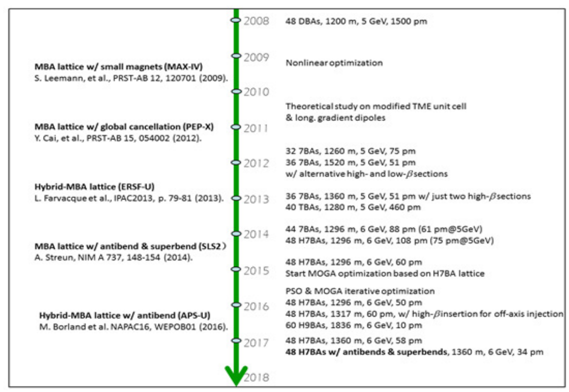

Figure 1: Evolution of the HEPS lattice over the past ten years. The figure also shows several project designs in the world on the left side of the time axis.

Optimization studies [1] based on the HEPS lattice with 48 identical hybrid-7BAs show that there is a trade-off between the emittance (brightness) and the ring acceptance. If satisfying only the dynamic aperture (DA) requirement of on-axis swap-out injection, the HEPS ring emittance can be pushed 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. The main reason for this trade-off is that the beta function requirements for the DA and brightness optimization are different and even in conflict.

After discussing with beamline experts, we noticed that there are not so many users preferring high brightness as expected. Some users require high flux while not necessarily high brightness. And some users like wide covering range of the synchrotron radiation wavelength, and do not care much about high flux or high brightness. So we decided to look for an alternative high-low beta design. In

ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP2WB01

this way, we can further push the beta function of one straight section down to close the optimal values for the highest possible brightness, and match the beta function of another straight section to moderate values for a large enough dynamic aperture.

Furthermore, we systematically compared different ultralow-emittance unit cells (details will be shown elsewhere), and found that the unit cell with a longitudinal gradient dipole in the middle and horizontal focusing quadrupoles with small anti-bending angles on two sides (as proposed in [16]) has the largest potential to minimize the emittance.

These considerations, together, bring about the latest HEPS lattice with a natural emittance of 34 pm. The optical functions along one period (two 7BAs) are shown in Fig. 2.

One important property of this design is that it provides a flexible source for dipole beam lines. The dipole within the central unit cell is a longitudinal gradient dipole with highest magnetic field in its central slice. 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 from 0.5 to 3 T to provide X-rays with different critical photon energy, while causing little perturbation to the ring optics and nonlinear performance.

As shown in Fig. 3, the DA of the bare lattice is about 6 mm and 4 mm in *x* and *y* planes. The 'effective' momentum acceptance (considering the limitation of integer and half integer resonances [17]) is about 3%. When considering errors, after appropriate correction, the DA can be recovered to ~80% of that of the bare lattie.

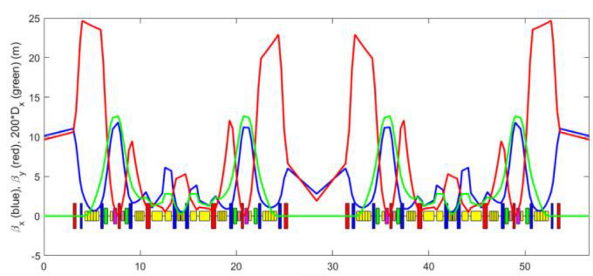

Figure 2: Optical functions along one period of the latest HEPS design.

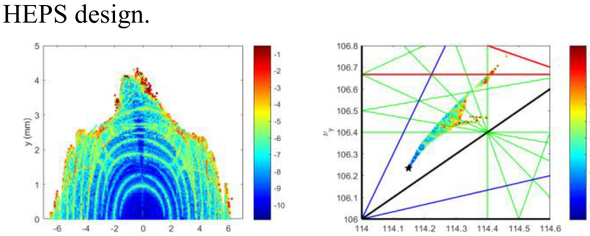

Figure 3: Dynamic aperture and corresponding frequency map of the latest HEPS design (bare lattice).

Injection to the Ring

We consider mainly the on-axis swap-out injection, while reserving possibilities for other injection schemes, especially the on-axis longitudinal injection (e.g., [18]). 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 lower energy of the booster ramping loop, we chose the 'high-energy accumulation' scheme. In this scheme, the booster at 6 GeV is used as a accumulator ring, and an extra transport line from the storage ring to the booster [19] is designed.

Especially for the high-charge mode, when the charge of the stored bunch of the ring reduces by a certain factor (e.g., from 14 nC to 12 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., 2 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 nC) is extracted from the booster and re-injected to the ring.

This scheme needs high transfer efficiency, e.g., at least above 90%, to avoid too much beam loss during this process. We are carrying out simulation studies with the aim to clarify the error tolerance for the elements of the injection, extraction systems and the transport lines.

Error Study and Lattice Calibration

In presence of typical alignment, magnetic field, and BPM errors, simulations indicate that it is very difficult 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 [20].

We have simulated the lattice calibration process [21] with the AT program. For the HEPS lattice, by looking inside the error sources, we found the nonzero offset in sextupole is main contributors of DA reduction. Thus we included the sextupole alignment in the lattice calibration simulation, which helps recover the nonlinear performance. Later we will include the insertion devices in the lattice model, and simulate the correction process.

Collective Effects

The fundamental frequency of the HEPS RF system is chosen to 166.6 MHz. To relieve 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. The bunch length can be lengthened by about 3 times.

For the latest lattice, assuming the coupling factor is 10%, the Touschek lifetime was evaluated, about 5 and 0.7 hours for the low-charge mode and high-charge mode, respectively. Regarding such a poor lifetime, top-up injection is necessary and is under study for the HEPS.

The impedance budget of the HEPS storage ring was estimated [22]. It was 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.

ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP2WB01

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

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 solved with a positive chromaticity. 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 (HOMs) of RF cavities and the resistive wall impedance (the full aperture of the vacuum chamber is on the level of 25 mm). In the storage ring, HOM damper has been carefully designed and optimized to damp the HOMs of the superconducting cavities. With the damped HOMs, we did not observe HOM induced coupled-bunch instabilities at 200 mA in macro-particle simulations. Nevertheless, to cure the instabilities and ensure stable operation, feedback system with damping time of shorter than 0.5 ms is required.

Injector Design

The HEPS injector consists of a linac and a booster. The booster will be located in a separate tunnel from the ring, in order to reduce the effect of the ramping cycle of the booster to the particle motions of the ring.

Inspite of the ‘high-energy accumulation’ scheme, it is still needed to store a bunch in the booster with a high enough charge, e.g., not less than 2 nC. To relieve the limitation due to collective effects, the linac energy was increased from 300 MeV to 500 MeV, and the booster lattice is changed from a 15BA to a FODO structure. The FODO lattice allows larger momentum compaction factor and a smaller average beta function, which is helpful to increase the bunch charge threshold at lower energy of the booster. As a price, the natural emittance of the booster at 6 GeV is increased from 4 nm to 40 nm.

CONCLUSION

After approximately ten years’ evolution, a storage ring lattice with a natural emittance of 34 pm was basically reached for the HEPS project. Based on this lattice, studies on related physics issues are underway. So far we did not find great risks. Nevertheless, there are many issues still need to be looked inside to finally reach a complete design for the HEPS project.

REFERENCES

[1] Y. Jiao, et al., “Status of HEPS Lattice Design and Physics Studies”, SAP2017, Jishou, Hunan, China, 2017.8.

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

[3] 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).

[4] Y. Jiao, G. Xu, and D.H. Ji, “Latest design and optimization of the PEPX-type lattice for HEPS”, SAP2014, Lanzhou, 2014.8.

[5] Y. Jiao, G. Xu, S.Y. Chen, Q. Qin, and J.Q. Wang, “Advances in physical design of diffraction-limited storage ring”, High Power Laser and Particle Beams, 2015, 27(04): 045108.

[6] G. Xu and Y.M. Peng, Chin. Phys. C, vol. 39, p. 067001, 2015.

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

[8] G. Xu, Y. Jiao, and Y. Peng, “ESRF-type lattice design and optimization for the High Energy Photon Source”, Chin. Phys. C, vol. 40, p. 027001, 2016.

[9] Y. Jiao, “Improving nonlinear performance of the HEPS baseline design with a genetic algorithm”, Chin. Phys. C, vol. 40, p. 077002, 2016.

[10] G. Xu, et al., “Recent Physical Studies for the HEPS Project”, IPAC2016, WEPOW026, Busan, Korea, 2016.5.

[11] Y. Jiao, et al., “Progress in the design and related studies on the High Energy Photon Source”, Physics Procedia 84, p. 40-46, 2016.

[12] 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).

[13] G. Xu, et al., “Progress of the Lattice Design and Physics Studies on the High Energy Photon Source”, IPAC2017, WEPAB052, Copenhagen, Denmark, 2017.5.

[14] Y. Jiao, S.Y. Chen, G. Xu, “Candidate HEPS Lattice Design With Emittances Approaching the Diffraction Limit of Hard X-Rays”, IPAC2017, WEPAB054, Copenhagen, Denmark, 2017.5.

[15] Y.M. Peng, et al., “The Off-Axis Injection Lattice Design of HEPS Storage Ring”, IPAC2017, MOPIK079, Copenhagen, Denmark, 2017.5.

[16] A. Streun, A. Wrulich, Nucl. Instr. Meth., A, Vol. 770, p.98-112, 2015.

[17] Y. Jiao, Z. Duan, and G. Xu, “Characterizing the nonlinear performance of a DLSR with the effective acceptance of the bare lattice”, IPAC2017, WEPAB055, Copenhagen, Denmark, 2017.5.

[18] G. Xu *et al.*, “On-axis beam accumulation enabled by phase adjustment of a double-frequency RF system for diffraction-limited storage rings”, IPAC16, WEOAA02, Busan, Korea, 2016.

[19] Y.Y. Guo et al., “High energy transport line design for the HEPS project”, IPAC17, MOPIK082, Copenhagen, Denmark, 2017.05.

[20] Y.L. Zhao et al., “First turns around strategy for HEPS”, IPAC17, MOPIK082, Copenhagen, Denmark, 2017.05.

[21] D.H. Ji et al., “Study of HEPS performance with error model and simulated correction”, IPAC17, MOPIK081, Copenhagen, Denmark, 2017.05.

[22] N. Wang et al., “Development of the impedance model in HEPS”, IPAC17, WEPIK078, Copenhagen, Denmark, 2017.05.