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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 a 34-pm, 1360-m storage ring light source being built in the suburb of Beijing, China. The HEPS construction started in mid-2019. While the physics design has been basically determined, modifications on the HEPS accelerator physics design have been made since 2019, in order to deal with challenges emerging from the technical and engineering designs. In this paper, we will introduce the new storage ring lattice and injector design, and also present updated results of related physics issues, including impedance and collective effects, lattice calibration, insertion device effects, injection design studies, etc.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, 1.3-km, ultralow-emittance storage ring light source being built in Beijing, China.

The HEPS Test Facility (HEPS-TF [1]), as the R&D project for HEPS, had been 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. Also, the accelerator physics design of the HEPS [2] was basically completed in 2018 after a series of iterations. Based on this design, the Preliminary Design Report (PDR) of the HEPS [3] was drafted, finalized and released in the same year. The construction of the HEPS started in mid-2019.

During subsequent hardware and engineering de-sign of the HEPS storage ring based on the PDR design, a few problems and challenges emerged. To mitigate these problems and challenges, modifications of the HEPS physics design have been made. The new storage ring lattice and injector design were frozen in 2020 [4-7]. Based on the new designs, we updated the results of the related physics issues, including impedance and collective effects, lattice calibration, insertion device effects, injection design studies, beam loss and collimation, etc. In addition, we initiated the work of commissioning software. In the following, we will introduce the latest designs and results of related physics studies. Finally, we would like to mention the explorative studies on longitudinal injection [8], round beam production [9, 10] and RF modulation in booster [11] related to the HEPS which, however, will not be further discussed in this paper.

LATTICE DESIGN & PHYSICS STUIDES

Storage Ring Lattice Design

In the PDR of the HEPS released in 2018, the storage ring lattice (referred to as V2.0 lattice) consists of 48 modified hybrid 7BAs, and results in a natural emittance of 34.2 pm [2, 12, 13]. Nevertheless, along with the progress of the subsequent hardware and engineering design, a few technical problems emerged (details can be found in [4]). It requires to (1) adjust the lengths of the drifts between adjacent magnets, so as to adapt to the current level of domestic accelerator technology, (2) change the upper limit of quadrupole gradient used in the lattice, to ensure that the maximum pole face field is approximately 1 T, and (3) decrease the bending fields of middle three dipoles of each 7BA for the ease of radiation shielding.

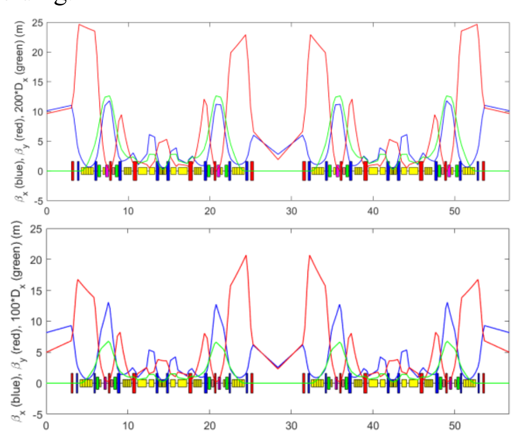

Figure 1: Optical functions and layout of one super-period of the PDR lattice (upper) and the V3.0 lattice (lower).

According to these new requirements, we updated the variation range of the magnet parameters and the drift lengths, and re-optimized the lattice with a combination of MOGA and PSO [14] and machine learning enhanced MOGA [15, 16]. After being optimized, a new version of the storage ring lattice was obtained, referred to as V3.0 lattice. Compared with the PDR lattice, the total length of drifts is increased by about 1.1 m per 7BA in the new lattice, as shown in Fig. 1. Although the modifications bring huge

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challenge to emittance reduction, through optimization the natural emittance just has a little increase from 34.2 pm·rad of the PDR design to 34.8 pm·rad of the new lattice. The price is smaller ring acceptance which, however, is still sufficient to meet the requirement of on-axis injection, with injected beam of smaller emittances thanks to re-optimization of the booster lattice [6].

Based on the new lattice, different models of combined function dipole were tested [17], and magnet models with more practical field distribution are under study.

Injection Design

The injection scheme of HEPS storage ring is on-axis swap-out injection, combined with high-energy accumulation in booster [18].

The injection and extraction design were updated in line with the modifications on the storage ring lattice, as well as updates from the hardware R&D and engineering aspects. A 5-cell stripline kicker module [19] is adopted in either of the injection and extraction region, together with Lambertson magnets tilted in raw, yaw and pitch.

The booster is also used as a full energy accumulator, to recycle and replenish the depleted bunch in the storage ring [18]. This scheme sets a constraint in the total length of the transport lines and the harmonic number of the booster and the storage ring, and also requires a delicate design of injection timing sequences [20]. A detailed end-to-end simulation of the whole injection process is under way, in order to ensure sufficiently high injection efficiency.

Besides, a pre-extraction kicker [21] was implemented in the extraction region to spoil the beam before extraction, to protect the septum in case of sudden kicker failures during extraction.

Injector Design

The injector is composed of a 500-MeV Linac, a 6-GeV booster and three transport lines. The injector design has been updated based on the PRD design [22-24].

As mentioned above, the adjusted storage ring lattice has a smaller DA compared to the PDR version. In order to ensure high injection efficiency, it needs to further reduce the emittance of the injected beam.

Besides, in 2019, it was determined to change the target current for the high-bunch charge mode at the initial commissioning stage from 200 mA to 70 mA. And, we changed the required maximum bunch charge from the linac and the booster to 7 nC and 5 nC, respectively. In this way, at the initial commissioning stage, it is not necessary to realize the "high-energy accumulation" in the booster of 6 GeV.

For the Linac, a new bunching system has been designed [25], which is composed of two sub-harmonic bunchers, a pre-buncher, a S-band buncher and a standard accelerating structure. The Linac design was re-optimized such that the bunch charge provided by the electron gun can reach up to 10 nC and the electron bunches at the exit of the Linac can reach bunch charge of up to 8.5 nC, with beam energy of 500 MeV and normalized emittance of 70 mm·mrad [5].

The HEPS booster was optimized based on the PDR version [3]. The latest lattice has a natural emittance of about 16.3 nm at 6 GeV [6]. A detailed impedance model, including the major impedance contributors has been developed based on the latest hardware designs. Simulations demonstrated that for the new booster lattice, one can inject a 7 nC bunch to booster without suffering single-bunch instability. With physical aperture, errors and impedance taken into account, transmission efficiency simulation of the booster injection (from linac) and ramping is under way. Details can be seen in [26].

And the transport lines were also adjusted [7] according to the design of the storage ring, booster and Linac. A dump was added in the ring-to-booster transport line to accept the extracted beam from the storage ring at initial commissioning stage.

Insertion Devices

In phase I of the HEPS project, it is planned to build 14 user beamlines and one test beamline. After iterative discussions with the beamline experts, types and parameters of all the insertion devices (IDs) have been basically confirmed [27]. It is worth mentioning that the impact of APPLE-Knot undulator [28] on the DA and beam lifetime is found to be significant if it is installed in a high-beta section. So, it was determined to put the this undulator in a high-beta section. Other measures like dynamics correction with current strips [29] are also considered for this undulator.

With the updated ID design, studies on the beam dynamics in the presence of IDs have been done. It is found that when considering IDs, DA reduction is ignorable while the beam life time is decreased by 1/3 compared to that of the bare lattice. And, high order field error specifications have been determined for IDs based on a comprehensive consideration on the numerical tracking results and performance measurements of prototype. It appears that among high order field components, skew sextupole component has dominating effect on the DA.

Error Studies and Lattice Calibration

Simulations had been performed to study the error effects, lattice calibration [30] and first-turn around [31]. We repeated the simulation based on the V3.0 lattice. The corrected beam parameter distortion is not significantly different from the results for previous version of lattice, and the dynamic aperture after lattice calibration can meet the injection requirements. The first-turn around simulation with more practical conditions is under way [32].

Collective Effects

For the impedance modelling and optimization, a more detailed impedance model of the storage ring has been developed, with main contributors covered. As the project proceeds, we got more involved with the engineering designs, including impedance evaluation for different hardware design schemes and timely responses to the engineering questions on impedance and instability (see,

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e.g., [33, 34]). Impedance optimizations and measurement were performed on key elements [35]. Also, the CSR impedance in the bending magnets and insertion devices are calculated and show no significant influence on the collective instabilities [36].

With the updated impedance budget, the impedance driven collective instabilities will be re-simulated, where the combined effects from feedback system and chromaticity in mitigating instabilities will be also studied.

A simulation code was developed to study the beam ion effects [37]. Simulations show that the instability is most serious at low beam current during commissioning, and a bunch-by-bunch feedback is effective to suppress the instability.

Beam Loss and Collimator Design

The collimator simulation for Touschek scattering particles were performed based on the V3.0 bare lattice and lattices with errors. The design targets of the collimator include: over 70% of the lost particles locate on the collimators, less than 20% of the particle losses take place in the straight section, and the decrease of the Touschek lifetime (due to introduction of the collimators) is less than 30%. From simulation results, it was determined to adopt 4 collimators evenly distributed in the storage ring, each of which is located at the dispersion bump in the upstream of high-beta straight section. The nominal collimator aperture was determined to be 4.0 mm, and the minimal aperture was set to 3.5 mm to reserve the space of adjustment [38].

The collimators also serve as beam dumps when machine protection system is triggered during normal operation. The beam power density deposited on the collimator is so high that it may cause damage to the collimator jaw. To avoid this, the collimators were designed to be adjustable vertically in a range of ±1 mm. And two pre-dump kickers were used to kick bunches and decrease the beam density during the beam dumping process. Simulations show that with two pre-dump kickers, the peak power density deposited on the collimator can be reduced to a few tenths of that without pre-kickers [39].

Beam Orbit stability

The beam orbit stability requires that the rms position and angular motion of the electron beam should be less than 10% of the beam size and divergence in transverse plane for the insertion devices and vertical plane for bending magnet sources. For HEPS, this corresponds to orbit fluctuations tolerance of 1 μm in horizontal and 0.3 μm in vertical plane, respectively.

To estimate the orbit fluctuation, we calculated the orbit motion induced by two major sources: the ground vibration and power supply ripples. The orbit motion was calculated with the ground vibration spectrum and the resonance model of the girder, and noises in power supply. Details can be found in [40].

In order to attenuate the fast fluctuation of the beam orbit, a global fast orbit feedback system (FOFB) was proposed with an effective bandwidth of above 500 Hz, with correction frequency of about 22 kHz. Detailed simulation studies are under way to ensure the effectiveness and robustness of the FOFB system.

Initial Work on Commissioning Software

Earlier in 2021, the development of high level applications (HLA) for HEPS commissioning was fully launched. Python programming language [41] was chose for graphical user interface (GUI) application development. The HLA for HEPS was classified in three categories: monitoring applications, applications for measurement, model-based applications for control and calculations. For monitoring and measurement GUI applications, there are rich of modules in python to meet the demand. For model-based applications, Elegant [42] and Ocelot [43] were considered as candidates to implement online calculations. A client-server framework was proposed for online calculations and always-running programs such as slow orbit feedback. The real calculation process is on the server side and the client is responsible for tuning calculation parameters.

SUMMARY

The HEPS construction has started since 2019. In the past two years, the HEPS physics design was continuously evolved and gradually frozen. In the next few years, the focus will be moved to commissioning related issues.

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