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BEAM DYNAMICS STUDY IN THE HEPS STORAGE RING*

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Abstract

The High Energy Photon Source (HEPS) is the first high-energy diffraction-limited storage ring (DLSR) light source to be built in China, with a natural emittance of a few tens of pm rad and a circumference of 1360.4 m. After 10 years' evolution, the accelerator physics design of the HEPS has been basically determined, with the ring consisting of 48 hybrid-7BAs with anti-bends and super-bends. This paper will discuss the accelerator physics studies of the HEPS storage ring, covering issues of lat-tice design, nonlinear optimization, collective effects, error correction, insertion devices, 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.

Starting from the proposal of a DBA lattice with a natural emittance of 1500 pm at 5 GeV [1], the HEPS storage ring design has been evolved for about ten years [2]. In 2016, the HEPS Test Facility (HEPS-TF), the R&D project for HEPS, was officially started and completed in 2018. Under this project, the physics design of the HEPS storage ring was basically completed [3]. As shown in Fig. 1, HEPS consists of a 500-MeV linac, a booster that ramps beam energy up to 6 GeV, a storage ring, and three transport lines connecting the linac, booster and the storage ring. Present design of the HEPS storage ring consists of 48 modified hybrid 7BAs, promising a natural emittance of 34.2 pm at 6 GeV. Top-up injection and two typical filling patterns, i.e., high-brightness mode (680 bunches, 200 mA) and high-bunch-charge mode (63 bunches, 200 mA) are considered. In the following we will report the lattice design and nonlinear optimization of the HEPS storage ring, as well as the related beam dynamics issues.

LATTICE & BEAM DYNAMICS

Lattice Design

In DLSR designs, multi-bend achromats (MBAs), consisting of a few TME-like cells (the number is larger than 2) and two matching cells, are usually adopted to reach an ultralow emittance (see e.g., [4]). MAX-IV is the pioneer light source that first adopts 7BAs in its design [5]. Nevertheless, worldwide DLSR design experiences indicated that, when continuously pushing down the emittance of such a MBA lattice, stronger and stronger sextupoles are required to compensate for the increasing natural chromticities coupled with the decreasing dispersion function (see e.g., [6]). This causes great difficulty in reaching a compact design with ultralow emittance of a few tens of pm, which is especially true for high energy DLSRs. For instance, the natural emittance of the HEPS 7BA lattice is limited to about 90 pm [7].

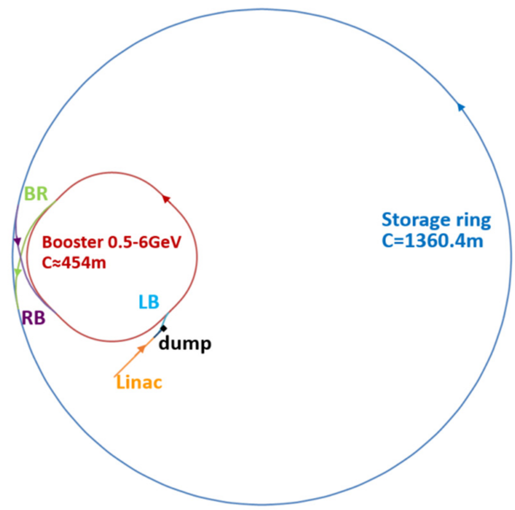

Figure 1: Schematic layout of the HEPS project.

To overcome this difficulty, the so-called hybrid-MBA lattice was proposed and first adopted in the design of ESRF-EBS [8-9]. Taking a hybrid-7BA as an example, it can be treated as a combination of two DBA-like cells and three TME-like cells. By putting all the chromatic sextupoles within the DBA-like cells where dispersion bumps are generated, the sextupole strengths can be kept to an acceptable level that can be reached using conventional magnet technology. Following this design philosophy, the natural emittance of the HEPS can be reduced to ~45 pm [10].

Using anti-bends in TME-like cells, allows independent control of the beta and dispersion functions, which helps to achieve even lower emittance. Anti-bends were first used in the SLS-2 design [11], where a novel unit cell consisting of antibends and longitudinal gradient bending magnets was proposed, resulting in a natural emittance of 137 pm at 2.4 GeV with a circumference of 288 m. It was then proposed to combine the anti-bends into the hybrid 7BA lattice in the APS-U lattice design [12]. By replacing three families of quadrupoles with anti-bends, the natural emittance was reduced from 67 pm to 45 pm.

In IHEP design [3, 13], besides using two families of anti-bends, the middle unit cell of the 7BA was also changed to be similar to that of SLS-2, i.e., the dipole is

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combined with longitudinal gradient rather than transverse gradient, and the corresponding transverse gradient is provided with a family of dedicated quadrupoles. Study showed [14] that the latter cell allows lower emittance, given a large enough cell length (e.g., 2.6 m for HEPS-like parameters). On the other hand, in such a design, the dipole has the highest field in its central slice. The central slice itself can severe as a bending magnet (BM) source. It is not necessary to reserve space for dedicated BM sources [15]. Furthermore, as long as the length and total bending angle of this dipole are kept the same, the peak field of the central slice can be changed, generating flux with different critical photon energy while causing little perturbation to beam dynamics.

In addition, from brightness optimization point of view (see Fig. 2), low beta functions of close to 1 m at the centre of insertion device (ID) sections are preferred. On the other hand, experience appears that it is very difficult to reach a large enough ring acceptance with such low beta functions in ID sections. To this end, high- and low-beta sections were designed on different sides of the 7BA. In this way, one can achieve as high brightness as possible in half of the ID sections. The price is that in the other ID sections one can pursue only high flux (the flux does not depend on beta functions). The layout and optics of the latest design of the HEPS storage ring are shown in Fig. 3. The main parameters of the ring are listed in Table 1.

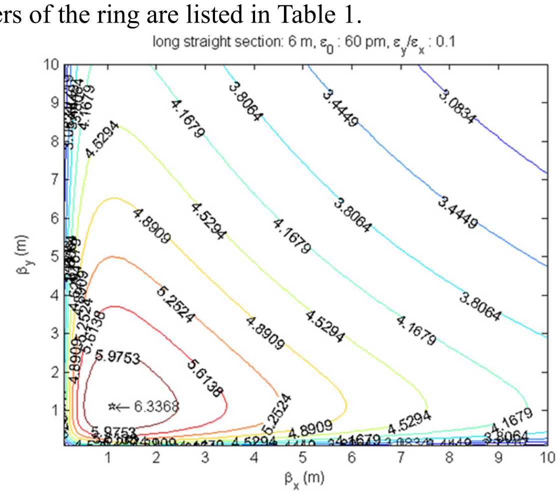

Figure 2: Brightness with respect to beta functions in the middle of the ID straight section, with fixed beam parameters, and with undulator parameters optimized at photon energy of 20 keV.

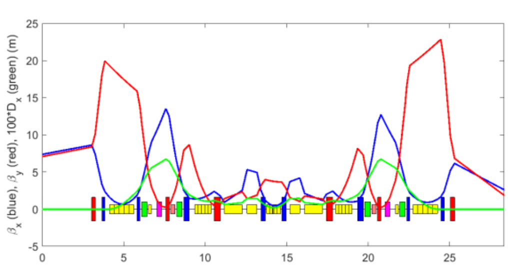

Figure 3: Optical functions and layout of one 7BA of the latest HEPS storage lattice.

Table 1: HEPS Lattice Parameters

Parameters	Values
Energy E_0	6 GeV
Beam current I_0	200 mA
Circumference	1360.4 m
Natural emittance ε_{x0}	34.2 pm.rad
Working point υ_x/υ_y	115.17/104.30
Corrected chromaticities (H/V)	+5/+5
No. of superperiods	24
ID section length L_{ID}	6 m
Beta functions at ID sect. (H/V)	2.6/1.9;7.4/7.1 m
Energy loss per turn	2.65 MeV
Rms energy spread	1.0×10^{-3}
Momentum compaction	1.88×10^{-5}

Nonlinear Optimization

Experiences suggested that the space for parameter choice to achieve an optimal performance is quite limited in a DLSR design and, the nonlinear dynamics in a DLSR is more coupled with the linear optics compared to a third generation light source. Furthermore, it is hard (if not impossible) to find one or a few factors that are effective in optimizing the dynamic aperture (DA) and momentum acceptance (MA) [16]. Thus, in HEPS design we per-formed tracking-based optimization with a rational combination of PSO and MOGA, which has been demonstrated to be more effective than either of them alone in approaching the true global optima of a typical explorative multi-objective problem with many local optima [17].

In the optimization, all tunable parameters (more than 60 parameters) were scanned and as many as possible constraints and limitations were considered. Two optimizing objectives were used to characterize the overall performance of a lattice; one is the weighted brightness, and the other one is the weighted DA, which is actually the product of DA and MA obtained from numerical tracking, frequency map analysis and with some normalization treatment [18]. Through optimization it was empirically found that the nonlinear performance is more sensitive to the horizontal phase advance between the sextupole pair than to the vertical. When relaxing the limitation on the vertical phase advance, a stronger vertical focusing than usual was suggested for higher brightness and larger DA (see Fig. 4). In addition, with the obtained lattice, the DA and Touschek lifetime (depends on local MA instead of MA of a specific point) was also optimized, which allows to increase the Touschek lifetime by a factor of 2, as shown in Fig. 5.

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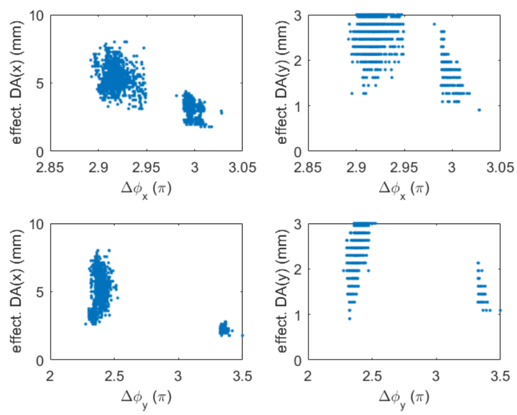

Figure 4: Phase advance between two focusing sextupoles in each 7BA of the found solutions without any constraints on the phase advance.

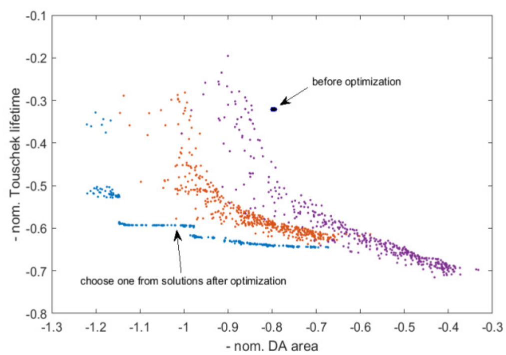

Figure 5: Optimization of the DA and Touschek lifetime, by varying only the multipole strengths.

Optics Correction with Errors

Since much stronger focusing is adopted in the HEPS design than that in the third generation light sources, optical deviations are more sensitive to errors, especially the transverse misalignments of magnets. To realize satisfactory beam stability, alignments of magnets on the same girder and between adjacent girders are required to be better than 30 µm rms and 50 µm rms, respectively.

A dedicated first-turn-around strategy has been developed to help find the closed orbit [19]. Optics correction simulations based on these error specifications were implemented. It was found that the beam orbit relative to the centre of sextupoles (hereafter referred to as “sextupole offsets”) is about 70 µm rms, which leads to a strong feed-down effect and makes the dominating contribution to the optics distortion. We proposed to install dedicated movers for each sextupole such that the transverse positions of sextupoles can be remotely adjusted with a high precision of 5 µm rms [20]. By using the sextupole offsets in the LOCO fitting [21], it is feasible to reach a very good correction of the linear optics and a substantial recovery of the DA.

The DA at the centre of the high-beta section and the LMA of the bare lattice were evaluated, where the multipole error effects were also considered. The results are shown in Fig. 6 and Fig. 7, respectively.

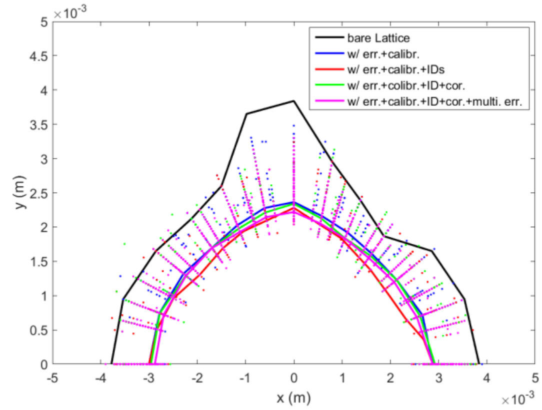

Figure 6: DAs of the HEPS storage ring, for the bare lattice, and for the case with practical errors. The colored curve represents the 20th-percentile smallest DA among the random error seeds.

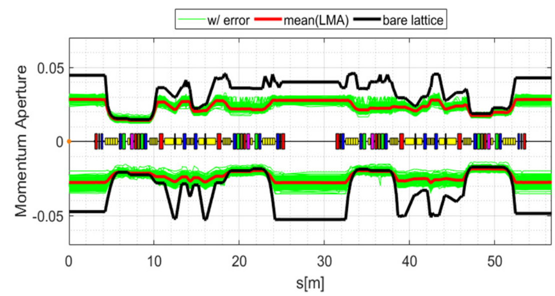

Figure 7: Local MAs of one super-period of the HEPS storage ring, for the case with the bare lattice and with practical errors.

Injection Design

These instructions are a typical implementation of the requirements. Manuscripts should ha The HEPS injection scheme is chosen to be the on-axis swap-out injection [22]. As shown in Fig. 8, the injection and extraction devices are located at two long straight sections that are separated by three 7BAs. 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 [23].

The injection process is illustrated in Fig. 9. First, one electron bunch that loses a fraction (e.g., 10%) of charge (blue) is extracted from the storage ring (a), injected to the booster after passing through a transport line (b), merged with one bunch of the booster (black) that has been injected from the linac and ramped up to 6 GeV (c); after about 10 thousands’ revolutions in the booster, this bunch (red) is then extracted from the booster (d), re-injected to the storage ring (f) after passing through another transport line (e). In this way, the booster needs only to store and accelerate bunches with a moderate charge, which can overcome the difficulty of storing a high-charge bunch in the booster due to single bunch instability that is particularly strong near the injection energy. In this way, the electron bunch of the storage ring is recycled, and at the low energy of the

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booster it needs only to store a bunch with lower charge than that in the ring.

It is required the rise and fall time should be fast enough and full width of the kicker pulse should be smaller than two times of minimum separation between two adjacent bunches. To somewhat release the technical challenge of the pulsed kicker, we choose 166.6 MHz as the fundament RF frequencies, with the corresponding requirement of the kicker pulse width of below 12 ns.

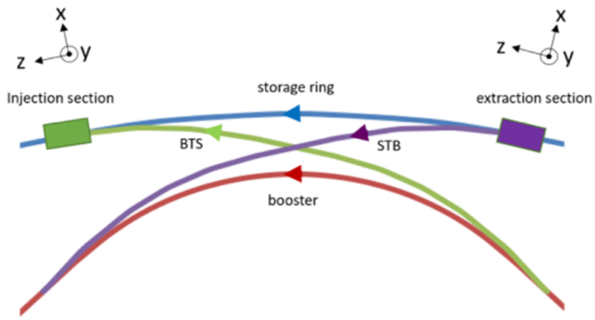

Figure 8: Schematic layout of the HEPS on-axis swap-out injection.

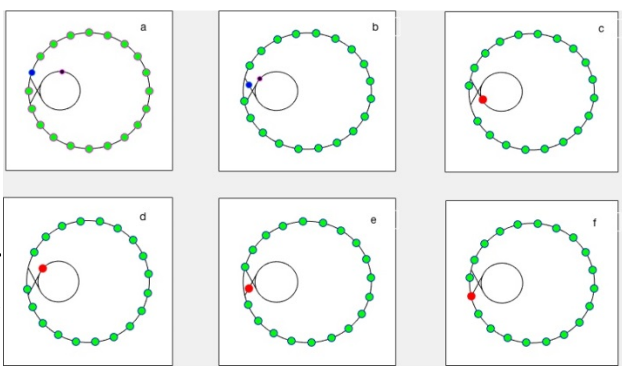

Figure 9: Process of replenishing a bunch in storage ring during HEPS operation.

Collective Effects and Beam Lifetime

In HEPS design, small aperture magnets and vacuum chambers are adopted. For most of the vacuum chambers, the inner radius is 11 mm, which induces much stronger impedance compared to the third generation light sources. The strong impedance, together with the ultralow emittance and small momentum compaction factor of the HEPS storage ring, make the collective effects, including the beam instabilities, intra-beam scattering (IBS), and Touschek scattering effects more significant.

To lower the particle intensity and mitigate the intra-beam scattering and Touschek effects, third harmonic cavities with frequency of 500 MHz are used for bunch lengthening. Such a choice potentially allows the possibility of longitudinal injection [24-26].

The longitudinal and transverse impedances of various vacuum components have been evaluated piecewise [27]. An impedance budget including all these elements has been obtained.

Single-bunch and multi-bunch instabilities have been evaluated based on the impedance budget [28-31]. The most important single bunch instabilities that affect the beam quality are the microwave instability in longitudinal plane and transverse mode coupling instability (TMCI) in transverse. The threshold of the microwave instability is about 2.2 nC, much lower than the bunch charge of high-bunch-charge mode, 14.4 nC/bunch. This will not cause beam loss but an evident increase in the rms energy spread, affecting the quality of the photon beam. For TMCI, it appears feasible to suppress the instability and keep beam stable at 200 mA with a large positive chromaticity.

On the other hand, the available highest beam current is mainly determined by the multi-bunch instabilities induced by the transverse resistive wall impedance and high-order modes (HOMs) of the RF cavities. The trans-verse resistive wall instability is induced by the resonance at zero frequency of the resistive wall impedance. For HEPS the growth time of the most dangerous instability mode is about 0.5 ms. A bunch-by-bunch transverse feedback system will be used to cure this instability. It was found that, the HOMs of 166.6 MHz RF cavities, if not well controlled, can cause instabilities with growth time beyond the ability of the state-of-art feedback sys-tem. HOM damper is necessary and now is carefully de-signed and optimized.

Associated with the small transverse beam size and high beam intensity, beam ion instability may be excited by the residual gas accumulated in the potential well of the electron beam and affect the machine performance. Both analytical estimation and numerical simulations were performed [32]. Studies showed that growth time is about 2 to 4 ms, which can be cured with the transverse feedback system.

For HEPS, the beam lifetime is mainly dominated by the Touschek lifetime. Based on the 10th-percentile smallest LMA among random error seeds, the Touscheck lifetime was estimated to 4.0 h for the high-brightness mode and 0.9 h for the high-bunch-charge mode. The vacuum lifetimes due to elastic gas scattering and gas bremsstrahlung, assuming a vacuum pressure of 1 nTorr (with 80% H2 and 20% CO), were estimated to be 136.7 and 257.8 h, respectively. It is expect to have a beam lifetime of 3.8 h for the high-brightness mode and 0.8 h for the high-bunch-charge mode

Insertion Devices

In the first construction phase, 14 beamlines will be built. Different types of insertion devices (IDs), such as CPMU, in-vacuum and in-air undulators, APPLE-Knot undulator and wiggler, are considered, and their parameters were optimized according to user requirements. The available spectral brightness is shown in Fig. 10. Brightness of close to 4×1022 ph/(s·mm^2·mrad^2·0.1%BW) is expected at the photon energy of ~20 keV for HEPS operated in the high-brightness mode.

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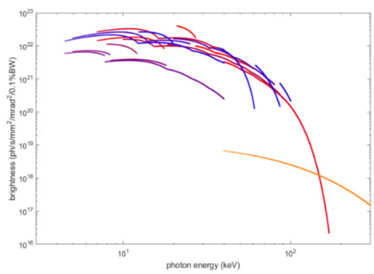

Figure 10: The available spectral brightness for HEPS operated in the high-brightness mode, evaluated by taking intra-beam scattering effect, impedance, and harmonic cavity into account.

CONCLUSION

The HEPS storage ring design with a natural emittance of 34 pm and solutions to the challenges inherent in this ultralow-emittance design are presented.

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