RECENT PHYSICAL STUDIES FOR THE HEPS PROJECT*

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Abstract

The High Energy Photon Source (HEPS), a kilometre-scale storage ring light source, with a beam energy of 5 to 6 GeV and transverse emittances of a few tens of pm.rad, is to be built in Beijing and now is under design. In this paper we reported the progress and status of the physical studies for the HEPS project, covering issues of storage lattice design and optimization, booster design, injection design, collective effects, error study, insertion device effects, longitudinal dynamics, etc.

INTRODUCTION

Early in 2008, a kilometre-scale storage ring light source with beam energy of 5 to 6 GeV, named the High Energy Photon Source (HEPS), was proposed to be built in Beijing [1]. Extensive efforts have been made on the lattice design and relevant studies of this project. The basic lattice structure has been continuously evolved, from DBA, standard 7BA, TBA, standard 7BA with high-gradient quadrupoles, to the 'hybrid' 7BA with high-gradient quadrupoles.

The concept of the hybrid MBA was first proposed [2] for the ESRF-U project. In a hybrid 7BA, the four outer dipoles are used to create two dispersion bumps with much higher dispersion functions than available in a standard MBA, and all the chromatic sextupoles are placed in the dispersion bumps, such that the sextupole strengths can be reduced to an achievable level with conventional magnet technology. In addition, the optics is matched to form a $-\boldsymbol{I}$ transportation between each pair of sextupoles, with phase advance at or close to $(2n+1)\pi$ (where n is an integer) in both x and y planes, so as to cancel most of the nonlinearities induced by the sextupoles.

An original hybrid 7BA design for the HEPS, with a natural emittance of 60 pm.rad, has been made [3]. The nonlinear performance of the lattice was measured with the 'effective' dynamic aperture (DA) and momentum acceptance (MA), within which it is required that not only the motion remains stable after tracking of a few thousand turns, but also the tune footprint is bounded by the integer and half integer resonances closest to the working point. For this design, it was found difficult to simultaneously obtain large effective DA (say, ≥ 2 mm) and MA (say, at the level of 3%). With the same lattice layout, by means of sextupole strength minimization together with tune space survey, we attained a better design [4] with a similar natural emittance, 59.4 pm.rad, but with larger MA (~3%) and DA (~2.5 mm in x and 3.5 mm in y plane), with the main parameters listed in Table 1. The physical studies up to date were mainly based on this design and will be reported below.

Table 1: HEPS Lattice Parameters

Parameters	Values
Energy E_0	6 GeV
Beam current I_0	200 mA
Circumference	1295.6 m
Natural emittance ε_{x0}	59.4 pm.rad
Working point υ_x/υ_y	116.16/41.12
Natural chromaticities (H/V)	-214/-133
No. of superperiods	48
ID section length L_{ID}	6 m
Beta functions at ID sect. (H/V)	9/3.2 m
Energy loss per turn	1.995 MeV
Rms energy spread	7.97×10^{-4}
Momentum compaction	3.74×10^{-5}

RECENT PHYSICAL STUDIES

Alternative Ring Design and Optimization

The potential of the hybrid 7BA lattice with small beta functions at insertion-device (ID) sections was explored with the particle swarm optimization (PSO) and multi-objective genetic algorithm (MOGA), by including all the tunable element parameters in optimizing variables. The performance of these two algorithms was compared, and it was found that a rational combination of MOPSO and MOGA would be more effective than using either of these two algorithms [5]. With such a procedure, we were able to find solutions showing trade-offs between the emittance and ring acceptance. Several candidate designs were found with a lower emittance and a larger MA (~3.5%) than the present design, which are more suitable for on-axis longitudinal injection. More details can be found in Ref. [6].

We also explored possible designs suitable for off-axis injection, where the beam is assumed to be injected off-axis by about 5 mm. To this end, we introduced a special designed high-beta injection section in order to achieve a DA of above 6 mm (considering the effects of lattice errors). Since HEPS is a green field machine, there can be some freedom in the lattice design to include a special designed injection section. We considered two schemes. One scheme is to just modify two standard 7BA cells to increase the beta-function (say, about 30~50 m) at the injection point while kept the circumference unchanged; and the other scheme is to insert two 2π sections in two

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opposite long straight sections of the ring with 48 identical hybrid 7BAs. In the latter case the circumference is enlarged about 4%, while the emittance remains the same. However, because of the high-beta injection section, the periodicity is broken. Simulations showed that the DA for on-momentum particles can almost be restored to what is expected with high-beta, while the DA for off-momentum particles drops significantly. Preliminary optimization showed that it is feasible to enlarge the MA by splitting sextupoles into more families. Further study is underway to look for designs with satisfying performance.

Booster Design and Optimization

The HEPS booster is assumed to be a 2 Hz synchrotron. Electron beam coming from a 300 MeV linac will be accelerated and then extracted and injected into the storage ring. There are two possible options for booster design. One option is to use a booster with smaller circumference than the ring and located in a separate tunnel and the other option is to use a booster in same tunnel as the ring.

The separate-tunnel design is a four-fold symmetry lattice with 4 nm-rad natural emittance for beam energy of 6 GeV. The circumference is about 432 m. Each superperiod consists of 13 identical TME cells and two matching cells to make dispersion-free long straight sections. More details can be found in [7].

The booster design sharing the same tunnel with the ring consists of 24 superperiods of FODO cells to fit the shape of the storage ring. The circumference is 1276.8 m with emittance of 2.3 nm.rad at 6 GeV. Fig. 1 shows the lattice of 1/24 of the booster and storage ring. The minimum distance from beam center to beam center is about 2.8 m and the maximum is about 3.2 m. The nonlinear optimization of this design is under way.

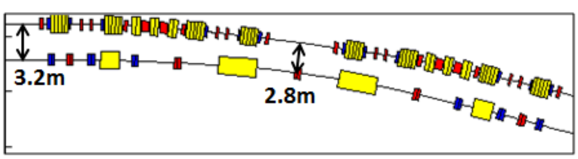

Figure 1: Layout of 1/24 of storage ring (outer) and booster ring (inner).

Injection Design

The very small dynamic aperture of the small-beta lattice design is not compatible with traditional off-axis injection schemes. Instead, the on-axis swap-out injection [8] is regarded as the baseline injection scheme. Moreover, a novel on-axis longitudinal injection scheme based on two active RF systems was proposed [9]. This scheme requires independent control of the RF phases of each cavity to conduct RF gymnastics: a second RF bucket is generated near each stored bunch during injection to enable beam accumulation, and the injected bunches can then be merged to the neighboring stored bunches. Injection simulations showed satisfactory injection efficiency with typical lattice errors. The on-axis injection schemes require a fast injection kicker with the state-of-art technology. On the other hand, off-axis injection utilizing a pulsed multipole magnet [10] is also an option if the lattice with a special designed injection section could achieve a large enough dynamic aperture.

Longitudinal Dynamics

For the HEPS design with low beta functions at ID section, it requires double-frequency RF cavities for longitudinal injection [9] and for lengthening the electron bunch for released collective effects. While for the candidate design for off-axis injection, double-frequency RF cavities are also required to achieve a long bunch for released Touschek and intrabeam scattering effects [11, 12].

Three candidate RF configurations were considered. They are with frequencies of 100 and 300 MHz, 166 and 500 MHz, and 500 and 1500 MHz. For all configurations, the RF parameters were tuned to provide a RF bucket height of 3.5%. Nevertheless, the momentum acceptance is limited by transverse dynamics (to ~3% for the present design). In the calculation, it was assumed 90% of the buckets are equally filled with electrons with an average beam current of 200 mA, and the coupling between transverse planes is 10%. The results are listed in Table 2.

Table 2: Beam Parameters for different RF configurations

Cases	RF_{100}	RF_{100}^{300}	RF_{166}	RF_{166}^{500}	RF_{500}	RF_{500}^{1500}
V(MV)	2.44	0.4	2.64	0.53	3.45	0.91
$N_0(10^9)$	13.9	13.9	8.34	8.34	2.77	2.77
σ_{s0}(mm)	7.84	51.3	5.49	32.1	2.48	12.1
ε_{x0}(pm)	54.6	54.6	54.6	54.6	54.6	54.6
σ_{s_IBS}(mm)	8.46	52.2	5.88	32.7	2.62	12.3
$\sigma_{\delta\_\mathrm{IBS}}(10^{-4})$	8.61	8.12	8.56	8.12	8.43	8.09
$\varepsilon_{x\_\mathrm{IBS}}$(pm)	68.9	57.3	67.5	57.2	65.0	56.9
τ_t(h)	3.07	17.2	3.50	17.9	4.60	20.1

Note: *$RF_{\#\#\#}$ means there is only the main frequency cavity, :$RF_{\#\#\#}^{\#\#\#}$ means that it contains both the main and higher harmonic cavities. The voltage of the $RF_{\#\#\#}^{\#\#\#}$ column is the voltage of higher harmonic cavity.*

Error Study and Lattice Calibration

Because of the strong quadrupoles and sextupoles in a DLSR design, the residual orbit and optics deviation will cause considerable effect on beam performance, which make the lattice calibration to be an important and essential issue. Therefore it is essential to evaluate the ring performance in presence of various errors to check the robustness of the present design. Also, the simulation of error effect can provide the guideline to restrict the manufacture redundancy of the hardware.

At present, the HEPS error study covered some common errors in practical accelerator as below (In brackets is typical setting in simulation):

- Alignment error in three directions (30 µm) and rolling angle (100 µrad);
- Field error of bending magnet (1e-3), quadrupole magnet (2e-4) and sextupole magnet (1e-3);
- Multipole field error of magnet (1e-3);
- BPM solution in calibration (0.5µm).

Many random seeds for errors were generated in same condition. For each seed, the lattice was calibrated by

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means of response matrix. Performance parameters, including dynamic aperture, emittance, beam parameters, were recorded and analysed. It was found that for present error setting, the alignment error (30 μm) has dominant contribution to emittance growth and DA reduction. More details will be shown in [13].

Collective Effects

Interaction of an intense charged particle beam with the vacuum chamber surroundings may lead to collective instabilities under certain conditions. We have evaluated certain collective effects based on the beam parameters of the first case in Table 2 and those in Table 1.

Resistive wall impedance of the vacuum chamber with NEG coating was calculated according to the theory developed in Ref. [14]. The longitudinal and transverse impedance for different thickness of NEG coating were studied and compared with the impedance of single layer in Fig.2 and Fig.3. Both longitudinal and transverse impedances increase with the coating thickness.

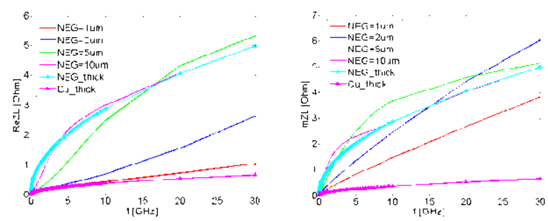

Figure 2: Longitudinal impedance for different thickness of NEG coating (Left: real part, Right: imaginary part).

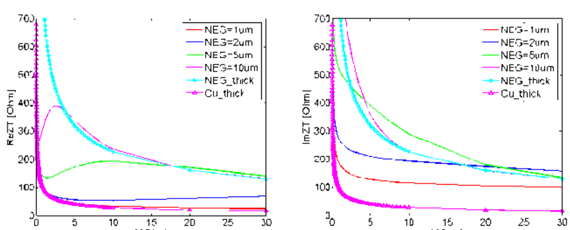

Figure 3: Transverse impedance for different thickness of NEG coating (Left: real part, Right: imaginary part).

The longitudinal microwave instability was estimated according to the Boussard or Keil-Schnell criterion [15, 16]. With the design bunch current, the criterion gives threshold longitudinal impedance of $|Z_{//}/n|$=28 mΩ, implying that the impedance of the vacuum component should be well controlled.

The threshold of the transverse mode coupling instability was calculated with the method of Eigen mode analysis. Considering only the resistive wall impedance of the vacuum chamber, the analysis gives threshold bunch current of 0.56 mA. The transverse resistive wall instability was also estimated. The growth time for the most dangerous instability mode is 0.8 ms. Transverse feedback system is needed to damp the instability, and positive chromaticity is also beneficial to suppress certain instabilities.

Insertion Device Effects

In contrast to conventional magnets, IDs have a complicated three-dimensional field distribution and the dynamic behavior is dominated by the so called dynamic kicks introduced by the oscillating electron trajectory in the periodic undulator or wiggler fields.

A symplectic tracking method [17, 18] based on analytic field description was applied in the particle tracking program. It was found that the vertical tune shifted by 0.003 due to eleven IDs in the ring. Nevertheless, the tunes can be recovered by adjusting the strengths of two families of adjacent quadrupoles.

The frequency map analysis of HEPS storage ring with eleven planar IDs was also taken. It indicated a significant reduce of dynamic aperture in vertical direction. The exact field of IDs was modeled and the dynamics effect was studied. It was found the horizontal dynamics would also be perturbed. More detailed study is underway.

Other Studies

Studies showed that half integer resonances can be excited with tiny focusing errors, causing particle loss. It appears that the 'effective' MA or DA for the ideal lattice gives a reasonable measure of practical ring acceptance.

REFERENCES

[1] X. Jiang *et al.*, "BAPS Preliminary Design Report", internal report, 2012.

[2] L. Farvacque *et al.*, in *Proc. IPAC'13*, pp. 79-81.

[3] G. Xu, Y. Jiao and Y. Peng, *Chin. Phys. C*, 40 (2): 027001.

[4] Y. Jiao, *Chin. Phys. C*, 40 (7): 077002.

[5] Y. Jiao and G. Xu, "Comparing the performance of MOGA and MOPSO in optimization of the HEPS performance", presented at IPAC'16, Korea, May 2016, paper HPMB019.

[6] Y. Jiao and G. Xu, "Exploring the ultimate linear and nonlinear performance of the HEPS hybrid 7BA design", presented at IPAC'16, Korea, May 2016, paper WEPOW025.

[7] Y.M. Peng *et al.*, "Candidate booster design for the HEPS project", presented at IPAC'16, Korea, May 2016, paper THPMB018.

[8] L. Emery and M. Borland, in *Proc. PAC'03*, pp. 256-258.

[9] G. Xu *et al.*, "On-axis beam accumulation enabled by phase adjustment of a double-frequency RF system for diffraction limited storage rings", presented at IPAC'16, Korea, May 2016, paper WEOAA02.

[10] Y. Jiao and G. Xu, *Chin. Phys. C*, 37 (11):117005.

[11] P.F. Tavares *et al.*, *Journal of Synchrotron Radiation*, 2014, 21: 862-877.

[12] S.K. Tian, J.Q. Wang, G. Xu *et al.*, *Chin. Phys. C*, 37 (6):067001.

[13] D.H. Ji, Y. Jiao, G. Xu, "Error study on a recent HEPS low-beta design", presented at IPAC'16, Korea, May 2016, paper THPMB017.

[14] N. Wang and Q. Qin, *Phys. Rev. ST Accel. Beams*, **10**, 111003 (2007).

[15] E. Keil and W. Schnell, CERN Report, TH-RF/69-48 (1969).

[16] D. Boussard, CERN LAB II/RF/Int./75-2 (1975).

[17] G.Wüstefeld *et al.*, in *Proc. PAC'95*, pp. 2868–2870.

[18] J. Bahrdt and G. Wüstefeld, *Phys. Rev. ST Accel. Beams*, 14, 040703 (2011).