THE PROGRESS OF HEPS BOOSTER DESIGN*

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Abstract

The High Energy Photon Source (HEPS), a kilometre-scale, ultralow-emittance storage ring light source, is to be built in Beijing, China. For HEPS, a full energy booster synchrotron operating at a frequency of 2Hz is considered. In this paper, we will report the progress of the lattice design and physics studies on HEPS booster, containing the injection consideration, ramping process, error studies, and so on.

INTRODUCTION

The storage ring light source HEPS is to be built in China. It will be composed of four main parts, a 0.3 GeV linac as the pre-injector, a full energy booster that accelerates the electron beam from 0.3 GeV to 6 GeV, a storage ring at 6 GeV and the radiation synchrotron experimental hall.

Now the R&D project for HEPS, the HEPS test facility (HEPS-TF) is underway. For the convenience of hardware R&D and related physics studies, a baseline storage ring lattice for the HEPS-TF was proposed [1-2]. It adopts the so-called 'hybrid' MBA concept that was first proposed for the ESRF-EBS project [3]. It has a circumference of about 1296 m and a natural emittance of about 60 pm at 6 GeV.

It is worth mentioning that the 60-pm lattice is not the final design for the HEPS, and extensive lattice design is underway with the aim to finally find an optimal lattice for the HEPS. Nevertheless, present physics studies including the booster design are based on this 60-pm lattice.

The 60-pm lattice was not dedicatedly designed for off-axis injection. The effective dynamic aperture is about ~2.5 mm. The present injection studies mostly focus on-axis injection schemes, including the longitudinal accumulation and swap-out schemes. Two filling patterns are mainly considered in HEPS storage ring, high-brightness mode (or low-bunch-charge mode, 90% buckets uniformly filled by 648 bunches with beam current of 200 mA) and timing mode (or high-bunch-charge mode, 60 bunches uniformly filled in the ring). For the latter filling pattern, we need inject 14.4nc charge to each bucket, this is a big challenge for injector, so, the booster also used for beam accumulation is proposed and we will introduce it in detail later.

After comparison the separate-tunnel design and the same tunnel design given in ref. [4], we found that the common tunnel didn't save money than built a separated tunnel. Considering the possibility of impact on storage ring from booster ramping and the conflict between ring construction and booster commissioning in same tunnel scheme, finally, we choose the separate tunnel.

In this paper, the booster lattice design is presented, and the physics studies containing the injection consideration, ramping process, error studies, etc. are also introduced.

LATTICE DESIGN

The magnetic lattice is a TME (theoretical minimum emittance) lattice. Its circumference is about 432 m, 1/3 of that of the storage ring. In each TME unit cell, we use two 1.4-m combined-function dipoles (with a small drift of 0.25 m in between) in the middle, to reduce the difficulty of fabricating a very long dipole. There are four 10.5-m dispersion free straight sections for installing RF cavities, injection and extraction systems. The optical functions and lattice structure is shown in Figure1 and the main parameters are listed in Table1.

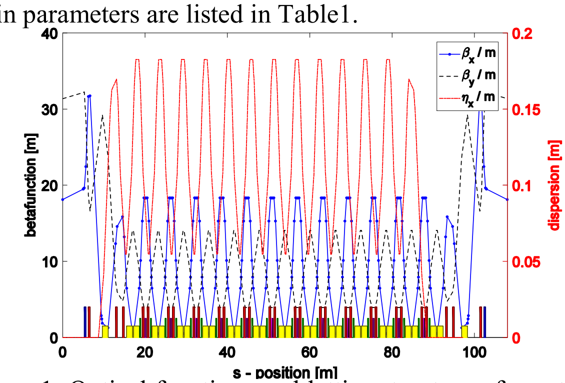

Figure 1: Optical functions and lattice structure of quarter of the booster.

Table 1: Main Parameters

Parameter	Unit	Value
Injection energy	GeV	0.3
Extraction energy	GeV	6
Number of super-periods		
Length of the straight sections	m	10.5
Circumference	m	431.8
Repetition rate	Hz	2
Emittance @ 6 GeV	nm.rad	4.5
Emittance @ 0.3 GeV	nm.rad	70
Tune(H/V)		26.30/8.13
Energy spread @ 6 GeV		0.0013
Energy spread @ 0.3 GeV		0.5%
Natural chromaticity(H/V)		-66.5/-20.5
Natural chromaticity(V)		-20.5
Momentum compaction factor		9.9E-4
Energy loss per turn @ 6 GeV	MeV	4.6
Long. damping time @ 6 GeV	ms	3.0
Hor. damping time @ 6 GeV	ms	2.1
Ver. damping time @ 6 GeV	ms	3.0
Maximum β_x/β_y	m	31.7/32.2

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We use four families of chromatic sextupoles to correct the chromaticity and to do nonlinear optimization. The nonlinear dynamics is simulated with the AT program. The DA of bare lattice and the chromaticity curve is shown in Figure 2, the acceptance is larger than the physical aperture (~13 mm radius).The transverse momentum acceptance is greater than 2%.

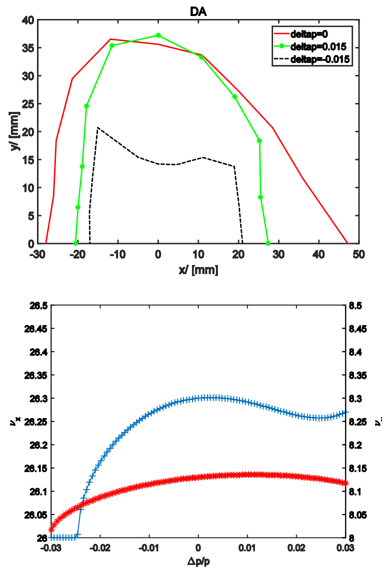

Figure 2: The DA and chromaticity curve of bare lattice.

ANALYSIS OF RAMPING PROCESS

Ramp Cycle

To meet the requirement of HEPS storage ring, a ramp cycle of HEPS booster is shown in Figure 3. The energy ramps up as the formula,

$$E(t) = \frac{E_{ext}-E_{inj}}{2}\left[\frac{E_{ext}+E_{inj}}{E_{ext}-E_{inj}} - Cos(5\,\pi\, t)\right], \qquad (1)$$

where E_{ext} is the extraction energy and E_{inj} is the injection energy.

Ramping curve has a flat bottom of 100 ms to store the injected bunches from the linac, and also a flat top of 100 ms to allow extraction of the bunches.

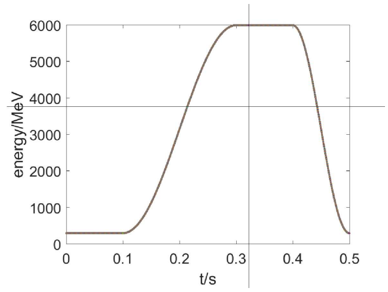

Figure 3: An energy ramp cycle in the booster.

Eddy Current Effect

Ramping in booster induces eddy current in the dipole vacuum chambers. This produces an effective sextupole field superimposed on the nominal dipole fields, leading to changes in the chromaticity, particularly an increased vertical chromaticity. The sextupole strength due to the eddy currents is calculated with the formula given in ref.[5], where we consider a stainless steel vacuum chamber of height g = 25 mm and elliptical aspect ratio g/w = 0.83. The induced sextupole strength is shown as a function of time, which is given in Figure 4. The sextupole strength induced by eddy current reached largest value at about 3GeV energy.

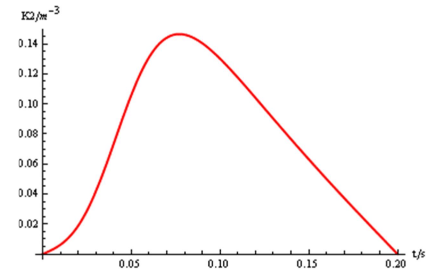

Figure 4: The sextupole strength induced by eddy current in ramping up process.

Emittance and Energy Spread Evolution

Beam energy spread and emittance evolution with energy ramping can calculate by the formula [6]

$$\frac{dA_i}{dt} = -A_i\left(\frac{\dot{E}}{E} + J_i\frac{P_\gamma}{E}\right) + C_q\frac{P_\gamma\,\gamma^2}{E}G_i \ , \qquad (2)$$

where A_i with i = 1 and 2 represents the energy spread $(\sigma_E/E)^2$and horizontal emittance ε_x, respectively. The first two damping terms in right hand side come from the adiabatic damping process which results from the evolution of the beam energy and the effect of radiation damping, and the last excitation term comes from the quantum fluctuation. J_i is the damping partition number, J_1 is the longitudinal damping partition, J_2 is the horizontal damping partition number. P_γ is the synchrotron radiation power, C_q=3.83*10^{-13}m. G_1=I_3/I_2, G_2=I_5/I_2, I_2, I_3 and I_5 are the synchrotron radiation integration. The emittance and energy spread evolution are given in Figure 5 and Figure 6, respectively. The results showed that as the energy is larger than 3 GeV, the emittance and energy spread reach the balance between radiation damping and quantum exciting.

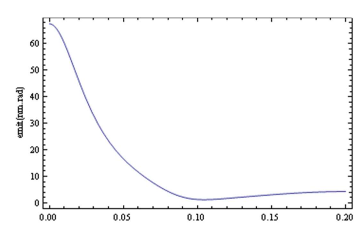

Figure 5: Emittance evolution in ramping.

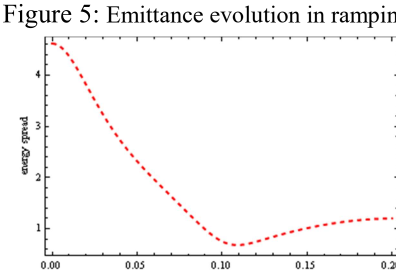

Figure 6: Energy spread evolution in ramping.

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RF Cavity

There are six 5-cell 499.8MHz RF cavities which offer a voltage of 6.2 MV and produce1% bucket height in extraction energy. The quantum lifetime is about 46 hrs.

At injection energy, we set the RF voltage to 0.3MV. The RF ramping up curve is shown Figure 7. In the progress, we keep the over-voltage factor 1.5.

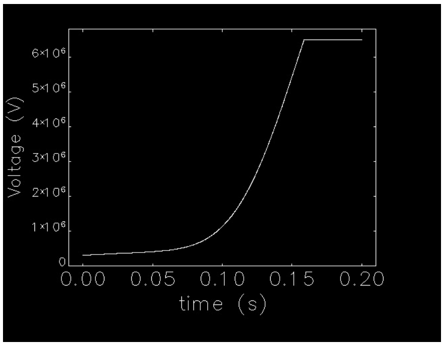

Figure 7: RF voltage during the energy ramp.

ERROR MODELING AND EVALUATION

Due to inevitable noise and practical errors, the status of areal machine will be different from the designed bare lattice. These differences can be treated as various errors on the bare lattice. Table 2 shows the preliminary error sheet. With these errors, the maximum COD is about 40 mm and 55mm in horizontal and vertical plane, respectively. After the correction with 56 correctors and 64 BPMs (with shift, gain and noise), the maximum CODs are corrected to less than 2mm. The results of COD before and after correction are shown in Fig. 8 and Fig.9, respectively.

Table 2：Preliminary Error Sheet

Parameter	Unit	Value
Transverse shift (x/y) of bend	mm	0.15
longitudinal shift (s) of bend	mm	0.15
Rotation around (x/y)of bend	mrad	0.2
Rotation around (s) of bend	mrad	0.1
Transverse shift (x/y) of Quad	mm	0.15
Longitudinal shift (s) of Quad	mm	0.15
Rotation around (x/y)of Quad	mrad	0.2
Rotation around (s) of Quad	mrad	0.2
Nominal field error of bend		0.1%
Nominal field error of Quad		0.1%

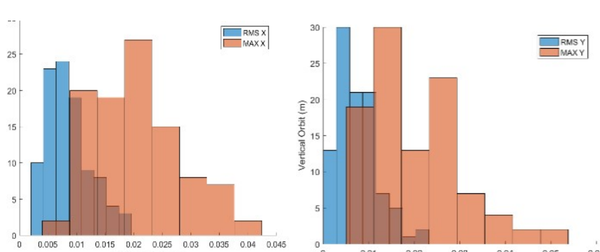

Figure 8: The Max and RMS COD before correction.

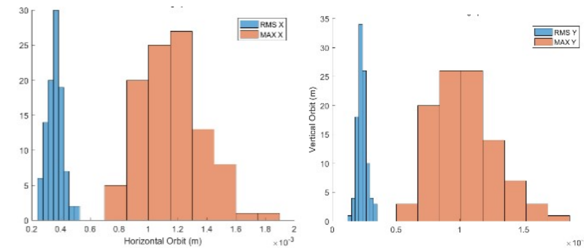

Figure 9: The MAX and RMS COD after correction.

BOOSTER AS AN ACCUMULATION RING

To meet the requirement of the high-charge bunch when the machine is operated in swap-out mode, the booster needs to have the ability of beam accumulation.

The accumulation process is realized with four steps, which is presented in figure 10. First, inject the required charge to booster from linac; the second, ramping up the booster energy to 6GeV; the third inject the beam knockout out from the storage ring to the booster and is merged with the existing beam; the fourth, after a few damping time, the accumulated beam with enough charge is extracted from booster and injected to storage ring.

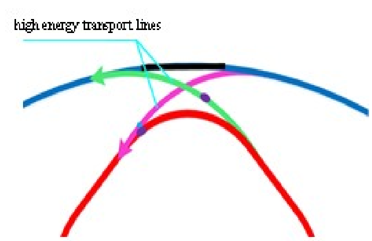

Figure 10: the diagram of on-axis swap-out injection schemes.

CONCLUSION

In this paper, we presented the lattice design, preliminary studies of ramping progress, errors and so on. To meet the injection requirement, the booster is also used for beam accumulation. There are still lots of work to do in beam dynamics in ramping and hardware error tolerance analysis.

REFERENCES

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

[2] L. Emery and M. Borland, *Proc. PAC'03*, Portland, OR, USA, 2003, pp. 256–258.

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

[4] G. Xu *et al.,* "Progress of the lattice Design and physics Studies on the High Energy Photon Source", Proc. IPAC'16, Busan, Korea, May 2016.

[5] "Effects of Eddy Current Induced Sextupole Moments in the Booster during Ramping", CLS Design Note - 3.2.69.2 Rev. 0.

[6] D. A. Edwards, M. J. Syfers, *An introduction to the Physics of High Energy Accelerators*. New York: John Wiley and Sons, Inc. 1993, p110-115.