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STATUS OF HEPS BOOSTER LATTICE DESIGN AND PHYSICS STUDIES*

Y.M. Peng†, Z. Duan, Y.Y. Guo, D.H. Ji, Y. Jiao, J.Y. Li, C. Meng, S.K. Tian, H.S. Xu, Key Laboratory of Particle Acceleration Physics and Technology, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Abstract

The High Energy Photon Source (HEPS) with an ultralow emittance is proposed to be built in Beijing, China. It will utilize a booster as its full energy injector. On-axis swap-out injection is chosen as the baseline injection scheme for the storage ring. As required by the storage ring, a beam with a bunch charge up to 2.5 nC is needed to be injected in the booster. However, limited by the transverse mode coupling instability (TMCI), such a high bunch charge is challenging. To overcome this problem, a lattice with a considerable large momentum compaction factor is designed. This paper reports the lattice design and physics studies of the HEPS booster, including injection and extraction design, error studies, eddy current effects, collective effects, and so on.

INTRODUCTION

The High Energy Photon Source (HEPS), based on an ultra-low emittance storage ring, is to be built in Beijing, China. It utilizes a 0.5 GeV linac and a 0.5-6.0 GeV booster as its full energy injector.

In the past two years, the main optimization goal of the HEPS booster was to reduce the emittance down to several nanometres. Several candidate lattices were proposed [1-3], and a 15BA lattice with combined function dipoles was chosen. This lattice had a natural emittance of about 4 nm and a momentum compaction factor of about 1×10^{-3}. Although having a very small emittance, a booster with this lattice cannot provide enough amount of charges in a single bunch for the storage ring.

The storage ring is aimed to have a natural emittance less than 60 pm at 6 GeV. With the present storage ring lattice, the emittance reaches 34 pm [4]. However, the dynamic aperture (DA) is not large enough due to strong nonlinear effects. Thus, it is not durable to accommodate the off-axis local-bump injection scheme, which is commonly used in the third generation light sources. Then, an on-axis swap-out injection scheme [5-7] is chosen for the HEPS storage ring. This injection scheme needs a very high bunch charge to satisfy the demand of a certain filling pattern of the storage ring.

Two filling patterns are mainly considered, the high-brightness pattern — 680 out of 756 buckets are uniformly filled with an average beam current of 200 mA, and the high-bunch-charge mode — 63 bunches uniformly filled in the ring also with 200 mA of beam current. For the latter filling pattern, the storage ring needs a bunch with 14.4 nC of charges from the booster, which is a big challenge for the booster to accumulate such a bunch charge at the injection energy. To overcome this problem, we design a scheme that the booster can used as an accumulator at the extraction energy.

When beam current in the storage ring decreases by a certain factor, a certain bunch is extracted and injected into the booster via a transport line. This bunch merges with an existing one already in the booster. After 3 times of damping time, the merged bunch is then extracted from the booster and reinjected into the storage ring via another transport line. Assuming when the total beam current decreases by 0.2% in the high-bunch-charge mode, and 94% of transfer rate in both of the transport lines, a bunch with 2.5 nC of charges is needed to be injected into the booster at the injection energy. However, in a booster with the 15BA lattice, the transverse mode coupling instability (TMCI) limits the single-bunch charge to reach this number at the injection energy. To overcome this problem, a momentum compaction factor larger than 3×10^{-3} is needed. A lattice using FODO cells is adopted to achieve such a momentum compaction factor.

In the following sections, the FODO lattice is presented. Based on this lattice, a number of beam physics studies, including injection and extraction design, analysis of ramping process, error studies, beam collective instabilities, are also reported.

THE BOOSTER LINEAR LATTICE

The booster adopts a traditional four-fold symmetric FODO lattice with single-function magnets. Each fold consists of 14 standard FODO cells and 2 matching cells. Its circumference is about 453.5 m, which is 1/3 of that of the storage ring. 2 kickers separated by a specially designed π section is used for the injection at 6 GeV. Compared with 4-kicker schemes, this arrangement has a smaller impedance and a lower cost. The optics functions is shown in Fig. 1. Some main parameters of the booster are listed in Table 1.

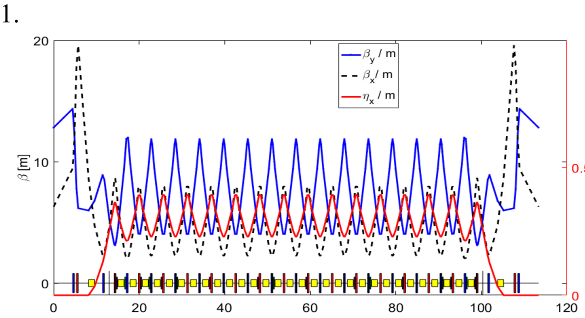

Figure 1: Layout of a quarter of the booster lattice.

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† pengym@ihep.ac.cn

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Six families of sextupoles are used to correct the chromaticity and perform nonlinear optimization. Under the bare lattice, the DA at the center of the long straight section is shown in Fig. 2, and the momentum aperture (MA) at same position is plotted in Fig. 3.

Table 1：Main Parameters of the HEPS Booster

Parameter	Unit	Value
Injection energy	GeV	0.5
Extraction energy	GeV	6
Length of the straight section	m	8.9
Circumference	m	453.5
Repetition rate	Hz	1
Emittance @ 6 GeV	nm.rad	37
Tunes(x/y)		16.83/10.73
Energy spread @ 6 GeV		9.6×10^{-4}
Natural chromaticity(x/y)		-18.5/-14.9
Momentum compaction factor		3.8×10^{-3}
Energy loss per turn @ 6 GeV	MeV	4.0
Damping time @ 6 GeV	ms	4.5/4.5/2.3
Maximum βx/βy	m	20/15

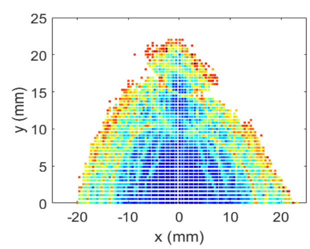

Figure 2: DA at the centre of long straight section.

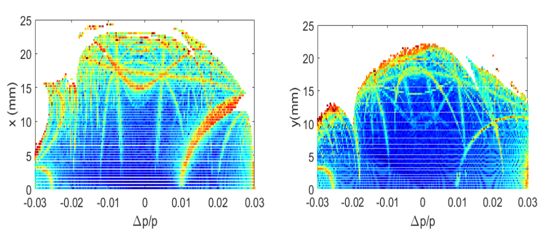

Figure 3: MA at the centre of long straight section. (Left) horizontal plane; (right) vertical plane.

This lattice is highly flexible and easy to be adjusted. The momentum compaction factor and the natural emittance can be compromised as shown in Fig. 4.

To get adequate transfer rate, the beam stay clear is defined as $\pm$ (5σ+5) mm. To reduce the impedance of the vacuum chamber and get higher bunch charge threshold, elliptical stainless steel chamber with aperture 36mm (H) ×30mm (V) is chosen.

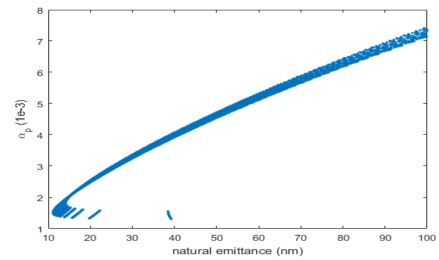

Figure 4: The momentum compaction factor as a function of the natural emittance.

INJECTION AND EXTRACTION

Single-turn injection is adopted for the HEPS booster at 500 MeV because of the long damping time. Vertical injection is used to send the beam from the linac into the booster. A vertical kicker is located at a quarter betatron oscillation period downstream to the injection point. A Lambertson septum is adopted for this low energy injection, also for the high energy injection and extraction. To accommodate this scheme, the orbit in the low energy transport line is about 20 mm lower than that in the booster.

The injection at 6 GeV is realized using an off-axis scheme with 2 vertical kickers separated by a phase advance of π in vertical direction. The booster and storage ring are in the same horizontal plane.

The extraction system is comprised of a kicker, a Lambertson septum and 4 bumpers. Detailed design of the high energy injection and extraction can be found in Ref. [8].

Filling Pattern and Injection/Extraction Timing

Two types of filling patterns are considered for the booster. One, with 2 bunches filled, is used to meet the demand of the high-bunch-charge mode of the storage ring. The other with 10 bunches filled is used for the high-brightness mode of the storage ring.

The energy ramping curve has a flat bottom of 200 ms for injecting up to 10 bunches from the linac. And a flat top of 200 ms to allow accumulating and extracting electrons at 6 GeV. Single-bunch extraction is used. The delay between two extractions is 20 ms. The high energy injection and extraction have a 12 ms (3 times of damping time) of separation. This process is shown in Fig. 5. More detailed introduction is presented in Ref. [9].

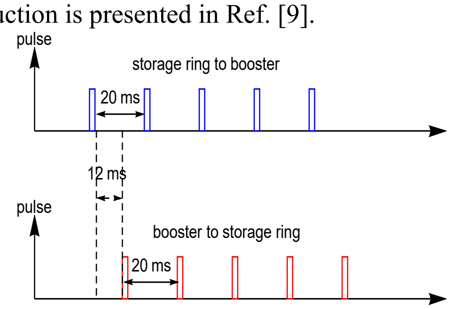

Figure 5: Pulse separations in the two high energy transport lines.

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ERROR STUDIES

Error effects and related corrections are studied for the HEPS booster [10]. Errors of the booster consists of static errors and dynamic errors. Static errors in our studies includes alignment errors and field errors. The induced closed orbit distortion (COD) and tune shift are corrected. 72 BPMs and 48 horizontal and 32 vertical correctors are adopted in the correction. After correction, the COD in most cases with random errors can be controlled within 1 mm.

A better than 300 ppm of tracking precision for power supplies is needed for the HEPS booster to avoid the tunes crossing dangerous resonance lines during ramping.

According to our simulation, multipole errors cause dynamic aperture reduction. In the simulations, random multipole errors up to 6th order with reasonable amplitudes are assumed. The results indicate that the dynamic aperture still fit the requirement of the injection.

Field uniformity of the extraction Lambertson and kicker could make the emittance of extraction beam grow. In our studies, all the field deviations are considered as a kick at the centers of the elements. To keep the emittance growth within 10%, the field uniformity of Lambertson needs to be better than 0.1% and the field uniformity of the kicker needs to be better than 2%.

ANALYSIS OF RAMPING PROCESS

The repetition rate of the HEPS booster is selected as 1 Hz. The duration of energy ramping up is 400 ms. The varying magnetic field generates eddy current in the vacuum chamber. The eddy current induced sextupole field is investigated. In our case, a stainless steel vacuum chamber with height g = 30 mm and elliptical aspect ratio g/w = 0.83 is used. The maximum value of sextupole generated by the eddy current is about 0.04. The chromaticity variation caused by this amount of sextupole field can be corrected and only has a very small impact on the dynamic aperture.

During the energy ramping, RF voltage is linear ramped up from1.2 MV to 8 MV simultaneously to keep a suitable bucket height. Simulation results indicate that these voltages allow a good injection/extraction efficiency and transfer rate during ramping.

BEAM INSTABILITY AND LIFETIME

Beam Instability

Beam instability study is more critical in the HEPS booster due to the high bunch charge, especially at injection energy. The detailed introduction of beam instability is expressed in Ref. [11].

The threshold of bunch charge is mainly determined by the transverse mode coupling instability (TMCI). For increasing the bunch charge threshold, we raised the injection energy from 300 MeV to 500 MeV, and use a long beam pulse with five short bunches from the linac. With these updates, the simulation results show the TMCI threshold at +1 chromaticity at 500 MeV is about 5 nC/bunch, which should fulfil the single bunch charge requirement by the injection of the storage ring.

The other limitation of the beam current is the coupled bunch instability (CBI) caused by high order modes of the RF cavity. Several experiments were carried out to study this issue.

We also estimated the microwave instability with multi-particle tracking under the two extreme conditions, at the injection energy and the extraction energy, respectively. No increase of the final energy spread can be seen.

Beam Lifetime

Beam lifetime in the storage ring is dominated by two beam loss-processes, the Touschek effect, and gas scattering, both elastic and inelastic.

The beam parameters used for Touschek lifetime evaluation at 500 MeV and 6 GeV are listed in Table 2. The local momentum aperture (LMA) used at 500 MeV is shown in Fig. 6. The LMA at the extraction energy is 0.96%.

Table 2: Parameters for Touschek Lifetime Evaluation

Parameter	500MeV	6000MeV
ε_x [nm]	41	37
σ_δ [10^{-3}]	5	0.96
σ_z [mm]	1.5	11.5
N_0[10^{10}]	1.55	9.3

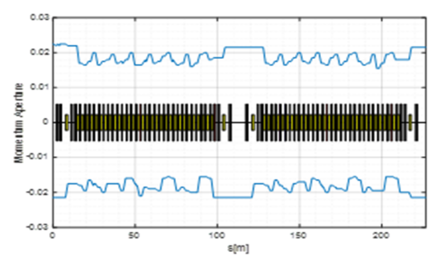

Figure 6: LMA of the HEPS booster at 500 MeV.

The residual gas scattering lifetime is calculated under an assumption that the pressure in the vacuum chamber is 20 nTorr (with 80% of H2 and 20% of CO) and the residual gas temperature is 293.15 K. The momentum aperture used for inelastic gas scattering lifetime calculation is considered the same as the physical aperture.

A summary of the beam lifetimes in the booster ring is given in Table 3. The total beam lifetime is about 0.6 hours at the injection energy, and about 7.4 hours at the extraction energy. A 10% of coupling of the horizontal and vertical emittance is used in the calculation.

Table 3: Beam Lifetime of the HEPS Booster

Energy	$\tau_{elastic}$	$\tau_{inelastic}$	$\tau_{Touschek}$	τ
500MeV	1.43	10.72	1.13	0.60
6GeV	209.9	9.08	50.75	7.43

SUMMARY

In this paper, the baseline design of the HEPS booster is proposed. Preliminary error studies, including COD correction, dynamic errors, and the impact of multipole errors

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on dynamic aperture, have been carried out. The eddy current effect during ramping is analysed. The beam lifetime is estimated.

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