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STUDY OF BEAM TRANSMISSION EFFICIENCY IN INJECTION AND RAMPING PROCESS OF THE HEPS BOOSTER*

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Abstract

A high-bunch-charge mode, with a bunch charge of approximately 14.4 nC at 200 mA, has been proposed for the storage ring of High Energy Photon Source (HEPS). In order to reduce the bunch charge requirement to the injector, “high-energy accumulation” in the HEPS booster is proposed to combine with the on-axis swap-out injection. This allows to reduce the requirement of bunch charge accelerated in HEPS booster (500 MeV-6 GeV) from over 14.4 nC to about 5 nC. It is expected that the overall transmission efficiency during the low energy injection and ramping process of the booster should be higher than 80% to fulfil the requirement. In this paper, we present the simulation results of transmission efficiency and potential improvement measures.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6 GeV, fourth-generation storage ring light source being built in the suburb of Beijing, China. The facility is comprised of a storage ring, a full energy injector, and dozens of beam lines.

HEPS storage ring [1, 2] has been designed with an ultralow emittance of tens of pm·rad by adopting the hybrid 7-bend achromat approach [3] with some special magnets, such as, longitudinal gradient bends (BLG) [4, 5], high gradient quadrupoles, anti-bends [6], and so on. An on-axis swap-out injection scheme [7] has been proposed for the HEPS storage ring.

The designed beam current of HEPS storage ring is 200-mA, and to meet the users’ requirements, two types of filling patterns are considered: the high-brightness mode (filling with 680 bunches) and the high-bunch-charge mode (filling with 63 bunches). To reach the designed beam current, the injector should provide electron beam with bunch charge higher than 14.4 nC to the storage ring, which is a great challenge to the design of Linac and booster.

In order to reduce the bunch charge requirement of HEPS Linac and relax the influence of the collective beam instability when the beam is injected to the booster from Linac, a “high-energy accumulation” scheme [8] in the HEPS booster has been proposed, which can reduce the requirement of bunch charge in HEPS booster (500 MeV-6 GeV) from over 14.4 nC to about 5 nC. The Linac and the low energy transport line (LB) are designed and optimized to deliver 7 nC bunch charge to the booster [9]. To fulfil the requirement of storage ring injection, the overall transmission efficiency (TE) including the injection and ramping process of the HEPS booster should be higher than 80%.

Along with the evolution of the design of the storage ring lattice and injection scheme, three versions of the booster lattices were proposed as follows: the version in the project proposal stage [10] (called V1.0), the version in the preliminary design report stage [8] (called V2.0) and the hardware fixed version (called V3.0) [11]. In the V3.0 booster design, FODO lattice is adopted, with a circumference of approximately 454 m and a horizontal natural emittance of below 20 nm.rad at 6 GeV. The booster and the storage ring are located in separate tunnels to minimize the influence of booster ramping on the beam dynamics of the storage ring.

Based on the V3.0 lattice, we optimised the Twiss parameters and slightly changed the tunes. The optimized lattice is called V3.1 lattice. In this paper, we present the simulated TE by using the V3.1 bare lattice and three lattices with typical error settings and corrections. The possible ways to improve the TE are also discussed.

SIMULATION CONDITIONS

In the simulation of the TE during low energy injection and ramping process of HEPS booster, we used the Elegant code [12] and the V3.1 lattice with an emittance of about 16.3 nm·rad and the tune of (21.15,11.21). The optics functions of one quartrant of the booster lattice are shown in Fig. 1.

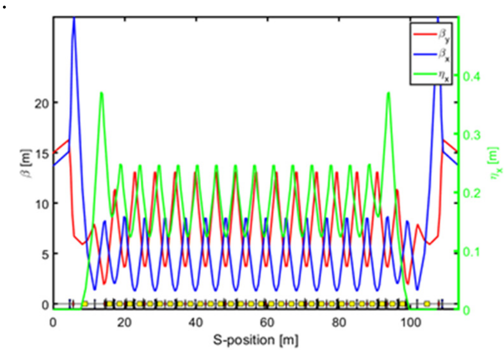

Figure 1: The optics functions of one quadrant of the booster lattice.

The repetition rate of HEPS booster is 1 Hz, and the ramping cycle is designed with a 200 ms flat-bottom and a 200 ms flat-top. To obtain a bucket which is big enough to capture the beam, the total voltage of RF cavities is linearly changed from 2 MV to 8 MV. In our simulation, we only considered the flat-bottom and ramp-up process. The changes of energy and RF voltage in a cycle are shown in Fig. 2.

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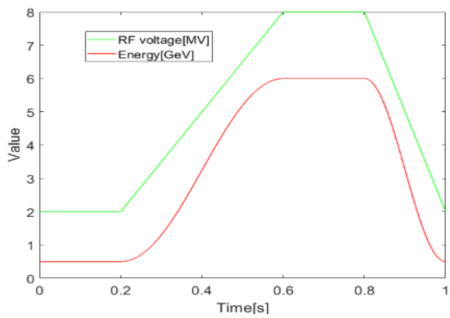

Figure 2: A schematic diagram of the energy change and RF voltage change in a booster ramping cycle (The red line is the energy curve, and the green line is the RF voltage curve).

To compare the TE in different conditions, the bare lattice with physical aperture and three lattices with static errors, orbit corrections and physical aperture were chosen.

The three lattices with errors and orbit corrections are:

- 314# lattice: with the biggest vertical closed orbit distortion (COD) and the smallest dynamic aperture in vertical plane.
- 247# lattice: with the biggest average orbit (the average value of the absolute value of all COD) in horizontal plane.
- 026# lattice: with the biggest average orbit (the average value of the absolute value of all COD) in vertical plane.

We also used two types of particle distribution. In the first type, the bunch contains 1000 random micro particles with Gaussian distribution (called the Gaussian beam); the initial RMS emittances are 80 nm·rad both in the horizontal and vertical planes, the RMS energy spread is 0.5% and the RMS bunch length is 3 mm; the beam is match to the phase space of the booster lattice. In the other type, it is the tracked beam distribution throughout the Linac and LB (called the simulation beam). The bunch contains about 50000 micro particles, in our simulation, we sampled 2% (about 1000 particles) for saving simulation time. The main beam parameters of two particle distributions are listed in Table 1.

Table 1: Main Parameters Comparation of the Two Particle Distributions

Parameters	Gaussian Beam	Simulation Beam
Betax	14.045 m	9.890 m
Betay	15.406 m	14.965 m
Emitx	73 nm.rad	128 nm.rad
Emity	76 nm.rad	109 nm.rad
Energy spread	0.5%	0.9%
Bunch length	3.0 mm	1.5 mm

SIMULATION RESULTS OF TE

The TE with the Bare Lattice

The TE with the bare lattice is shown in Fig. 3. The TEs with Gaussion and simulation beam are 100% and 97.6%, respectively. The different particle distributions has obvious influence on TE. The distribution of injected beams can be optimized by tuning the quadrupoles in the LTB. According to the simulation results, the particles lost mostly happen in the first 200,000 turns. In the following, the beam is only tracked in the first 200,000 turns, correspond to about 300 ms, to save simulation time.

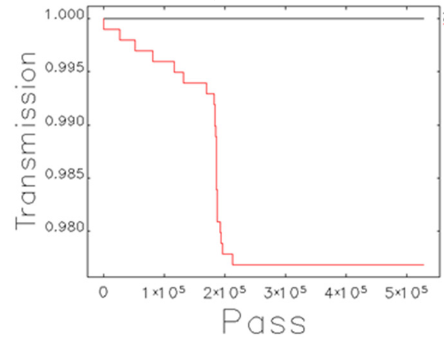

Figure 3: The TE results with the bare lattice (the black line is the result with Gaussian beam, the red line is the result with simulation beam, the horizontal axis is the number of passing turns and the vertical axis is the TE).

We analyzed the position of the lost particles, and found most of them are lost in the region with large horizontal beta function.

The TE in the Lattice with Static Errors and Orbit Corrections

To simulate the TE in the lattice including static errors and orbit correction, the 314# lattice, 247# lattice and 026# lattice are chosen. The simulated TEs with Gaussuian beam and simulation beam are shown in Figs. 4 and 5, respectively.

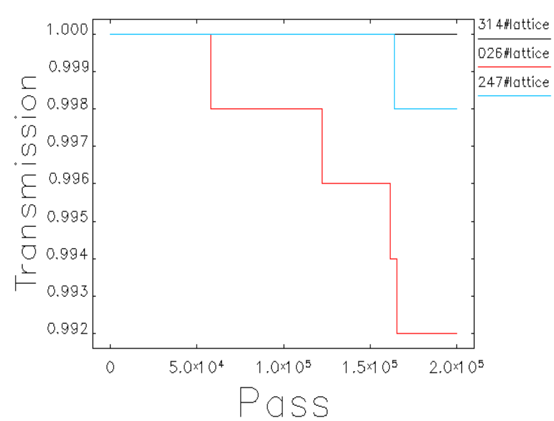

Figure 4: TEs simulated with Gaussuian beam (the black line is the result with 314# lattice, the red line is the result with 026# lattice, the blue line is the result with 247# lattice, the horizontal axis is the number of passing turns and the vertical axis is the TE).

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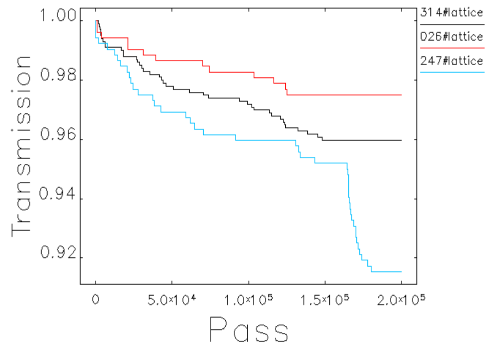

Figure 5: The TEs simulated with simulation beam (the black line is the result with 314# lattice, the red line is the result with 026# lattice, the blue line is the result with 247# lattice, the horizontal axis is the number of passing turns and the vertical axis is the TE).

The Effect of Tracking Errors on TE

During the booster ramping process, the asynchronism of the magenet power supplies cause tracking errors, which are dynamic errors and should be controlled to reduce their effects. It is necessary to evaluate the effect of the tracking errors to the TE. According to previous evaluations, it has been required that the tracking accuracy of the power supply is 300 ppm and can be relaxed to 500 ppm at 500 MeV. We simulated 20 seeds with the tracking errors of 500 ppm (random generated), in this simulation, Gaussion beam were used. Only 1 seed has 2 particles lost, other seeds have TEs of 100%. According to the TE simulation, it appears that the requirement of tracking errors is reasonable.

The Effect of Injection Orbit and Angle Deviation on TE

The beam is injected to the HEPS booster in vertical dimension. Here, we only simulated the effect of the vertical orbit and angle deviation to the TE. The amplitude stability of the kicker pulse is about ±0.5% and the time jitter is about 1 ns. Accordingly, the possibly kick angle deviation is about ±0.05 mrad. We set 3 cases with different orbit deviations and angle deviations to compare the effects on TE, the simulation results of TE with the 314# lattice and simulation beam are shown in Fig. 6. The injection_err1 means 0.5 mm orbit deviation and 0.1 mrad angle deviation, the injection_err2 means 0.5 mm orbit and -0.1mrad angle deviation, the injection_err3 means -0.5 mm orbit and -0.1mrad angle deviation.

According to the simulation results, the TEs with injection_err2 and injection_err3 are nearly same, but lower than injection_err1. And, the injection angle deviation has a larger influence on the TE. In future actual operation, we can adjust the strength of the injection kicker to improve the TE.

The Effect of Impedance on TE

In this simulation, the simulation beam and bare lattice were used. We added a 0.5 mm vertical orbit deviation. The simulation results with the detailed impedance model, including the major impedance contributors based on the latest hardware designs, are shown in Fig. 7. When the bunch charge reaches 10 nC, the TE decreases significantly. When the bunch charge is less than 8 nC, the impedance has little effect on the TE.

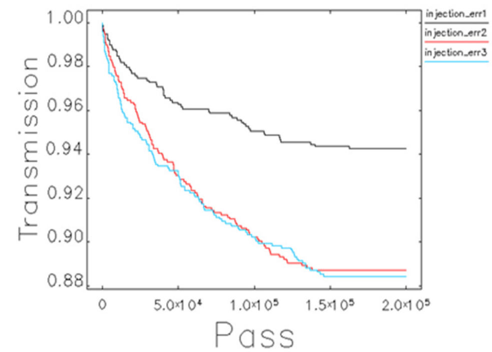

Figure 6: The TEs with injection errors (the black line is the result with injection_err1, the red line is the result with injection_err2, the blue line is the result with injection_err3, the horizontal axis is the number of passing turns and the vertical axis is the TE).

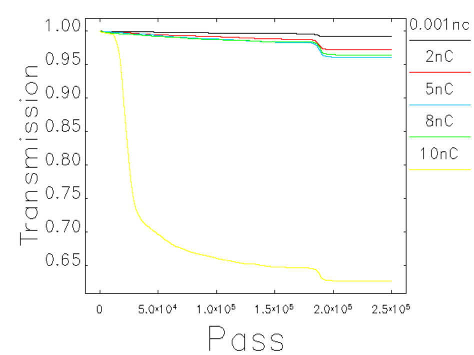

Figure 7: The TE results of different bunch charges with detailed impedance model simulated.

SUMMARY

This paper focus on the influence of different factors on TE in order to find possible effective ways to improve the TE. So, we simulated the TE of lattice with errors and without errors. The results show that the distribution of injected particles and the injection angle deviation have obvious effects on the TE. We can optimize the injection beam distribution by adjusting the strength of magnets in the LB and tuning the strength of injection kicker to reduce the injection angle deviation. When the bunch charge is less than 8 nC, the effect of impedance on the TE is little. In the simulation, it was assumed the tracking error does not change in the course of raising energy, and 500 ppm error was adopted, which may be slightly different from the actual situation (500 ppm tracking error in low energy stage and 300 ppm tracking error in high energy stage). However, this does not affect the presented deductions.

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