

# PROGRESS OF THE LATTICE DESIGN AND PHYSICS STUDIES ON THE HIGH ENERGY PHOTON SOURCE\*

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## Abstract

The High Energy Photon Source (HEPS) is a 6-GeV, kilometer-scale, ultralow-emittance storage ring light source to be built in Beijing, China. In this paper we will discuss the progress of the lattice design and related physics studies on HEPS, covering issues of storage ring design, booster design, injection design, collective effects, error study, insertion device effects, etc.

## INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, kilometer-scale, ultralow-emittance storage ring light source to be built in the northeast suburb of Beijing, and now is under extensive design.

As the R&D project for HEPS, the HEPS test facility (HEPS-TF) has started in 2016, and is to be completed by the end of Oct., 2018. The goal of the HEPS-TF project is to develop key hardware techniques that are essentially required for constructing a diffraction-limited storage ring light source, meanwhile, to complete the design for HEPS. We expect to obtain an ‘optimal’ lattice design for the HEPS, study the related accelerator physics issues and ensure there is no show-stopper from beam dynamics point of view, and give as detailed parameter list and tolerance budget table as possible for various hardware systems.

For the convenience of hardware R&D of the HEPS-TF, a baseline lattice of the storage ring was proposed [1-2]. It adopts the so-called ‘hybrid’ MBA concept that was first proposed for the ESRF-EBS project [3]. It consists of 48 identical hybrid 7BAs, providing forty-eight 6-m straight sections for insertion devices (IDs), RF cavities and injection system. The natural emittance is  $\sim 60$  pm.rad, and the circumference is  $\sim 1.3$  km (denoted as 60-pm lattice hereafter). For the injector, we consider to use a 300 MeV linac and a full-energy booster that accelerates the beam to 6 GeV.

For the 60-pm lattice, there is still much space to improve its performance. Actually, the lattice is continuously updated and optimized, by exploring and comparing different types of lattice structures and globally scanning all tuneable parameters of the ring with stochastic optimization methods. Nevertheless, the related accelerator physics studies, i.e., error simulation and correction system design, collective effects studies, injection and booster design, are now mainly based on the 60-pm lattice, with the aim to develop systematic and procedural analysis.

In the following we will briefly introduce the status of the lattice design, and report recent progress of studies on the related physics issues.

## RECENT PROGRESS OF LATTICE DESIGN AND PHYSICS STUDIES

### Ring Lattice Design

Efforts are made to continuously improve the storage ring lattice design based on the 60-pm lattice. We are now performing iterative and successive PSO (particle swarm optimization) and MOGA (multi-objective genetic algorithm) optimizations (following Ref. [4]) for several candidate lattice structures. It is expected to obtain several candidate lattices in this year, and then do a fair comparison to decide the final lattice for the HEPS. In the design and optimization, the circumference is assumed to be similar to the 60-pm lattice; instead of minimizing emittance, we try to optimize the brightness of the photon beam emitted from insertion devices; we use the effective ring acceptance of the bare lattice rather than the ring acceptance with errors as an indicator of the nonlinear performance of a lattice (see Ref. [5] for details); we are also looking for effective ways to separate different optimizing targets, e.g., maximum brightness and maximum ring acceptances.

On the other hand, since HEPS is a green-field machine, to achieve a better beam performance, we investigate the feasibility of designing a lattice with emittances approaching the diffraction limit of hard X-ray with typical wavelength of 1 Å, with details shown in Ref. [6].

The 60-pm lattice was not dedicatedly designed for off-axis injection. The effective dynamic aperture is about  $\sim 2.5$  mm. Correspondingly, the present injection studies mostly focus on-axis injection schemes, including the accumulation and swap-out schemes; and an active double-frequency RF system (166.6 and 499.8 MHz) is considered. Nevertheless, we are also exploring lattices with large enough dynamic aperture for off-axis injection with a specially designed high-beta injection section. A preliminary lattice design following this philosophy is described in Ref. [7].

### Injection Design

Based on the 60-pm lattice design, we are now mainly considering the on-axis swap-out injection and accumulation schemes.

In the swap-out injection scheme, a transport line (see Fig. 1) from the storage ring to the booster (BTS) has been designed to allow for accumulation of the extracted bunches from the storage ring in the booster at 6 GeV, so

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that a full charge linac or accumulation at the 300 MeV is not needed. Meanwhile, we are also discussing the feasibility of storing and accelerating a high-charge bunch in the booster. In this case, the BTS transfer line is not needed, but a stringent requirement on the performance of the linac and the booster is probably required.

For the on-axis accumulation scheme [8, 9] based on an active double-frequency RF system, recent studies indicate that the RF bucket to capture injected beam can be temporally later than the adjacent stored bunch bucket, to accommodate the fact that the fast injection kicker has a much smaller rise time compared to the fall time. As a result, the beam can be injected near the center of the bucket and the injection tolerances are almost the same as the swap-out injection schemes.

These two on-axis injection schemes share a compatible injection region design, and the injection simulation is underway to understand the hardware tolerances, as well as possible beam losses due to collective instability during injection.

### Injector Design

For the booster design, we mainly considered two options. One is to locate the booster and the ring in the same tunnel, while the other is to design a booster with circumference of about 1/3 of the storage ring and accommodate it in a separate tunnel.

Three candidate lattices were proposed [10, 11]. After a comprehensive discussion and comparison of these lattices, including the performance, cost, and related hardware fabrication issues, we choose a 15BA lattice as the nominal lattice for the HEPS booster. The booster is considered to be located in a separate tunnel, have 4 super-periods and a natural emittance of  $\sim 4.5$  nm at 6 GeV.

Based on the assumption of a sinusoidal energy ramping curve, we analysed the evolution of beam parameters and the eddy current effect (see Ref. [12] for details).

To simultaneously accommodate on-axis accumulation and swap-out injection schemes, two transport lines between booster and storage ring, named BTS and STB, were designed in a symmetric manner (see Ref. [13] for details), with the schematic layout shown in Fig. 1. In the accumulation scheme, only the BTS transport line is used. In the swap-out scheme, it is assumed the beam knock out from the ring is transferred to the booster through STB, merged with the existing beam of the booster, and then is re-injected to the ring through BTS.

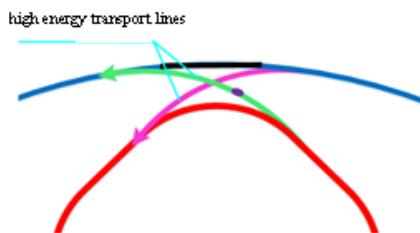


Figure 1: Schematic layout of the two beam lines between the booster and the storage ring.

### First Turns Commissioning

One important question is whether the beam can survive and be accumulated with such an ultralow-emittance design, when the beam is first injected into the HEPS storage ring in the early stage of commissioning.

To this end, we developed a program to simulate the commissioning strategy, in which the beam trajectory is corrected based on the analysis of response matrix. The simulation indicates that with the predetermined alignment errors and BPM noises, we can successfully store the beam in the ring up to a few hundred turns (see Ref. [14] for details). Next, we will study the commissioning of the first few turns, for several special cases, e.g., some BPMs or correctors are faulty or have extremely large errors.

### Error Study and Lattice Calibration

The performance of the ring is found to be very sensitive to errors, mostly because of the very strong quadrupole and sextupole magnets required by emittance minimization. To evaluate the ring performance and provide guideline to restrict the manufacture redundancy of the hardware, efforts are continuously done to simulate the error effects and lattice calibration process as close to the real circumstance as possible with the AT program.

Up to now, we have modelled the alignment errors of magnets and girders, BPM errors, main field errors and multipole errors of magnets in the lattice, and simulate the lattice calibration process, including correction of orbit, beta beating, dispersions, coupling and emittance. It is found that the misalignments of the focusing magnets have the most distinct influence on the optics. For present error setting and correction procedure, in most of the cases, DA of more than 2 mm can be obtained, which is acceptable to on-axis injection. The horizontal emittance growth can be kept below 10% with a probability of 90%, and the vertical emittance can be kept below 5 pm after vertical dispersion correction (see Ref. [15] for details). In addition, lattices with different sets of errors were generated for the convenience of other physics studies.

Further study will be done to obtain detailed tolerance budget table for various hardware systems.

### Collective Effects

For high intensity machines, the impedance can drive collective instabilities and limit the machine performance. The longitudinal and transverse impedance models are developed for various components of the main ring [16]. The broadband effective impedances are calculated. The main contributions to the longitudinal impedance are resistive wall impedance and elements with large quantity. And the transverse broadband impedance is dominated by the resistive wall impedance due to the small-aperture vacuum chamber.

Based on the impedance model, collective instabilities are studied with both analytical theory [17] and numerical simulations [18]. Two operational modes with different filling patterns are considered, i.e., low-charge mode (200

mA with 648 bunches) and high-charge mode (200 mA with 60 bunches). The possible collective instabilities during injection and operation are investigated separately.

Studies show that single bunch effects are critical for the high-charge mode during both injection and operation. A positive chromaticity is needed in order to damp the head-tail instability, transverse mode coupling instability, and transverse resistive wall instability. The longitudinal coupled bunch instability is more critical during operation with the lengthened bunch, since the synchrotron tune is smaller. Transverse and longitudinal feedback systems are required to damp the coupled bunch instability and the fast beam ion instability.

The Touscheck lifetime is calculated based on the MA calculation with errors (see Ref. [19] for details). The results indicate that it is feasible to achieve a Touscheck lifetime of above 36 hours for the low charge mode and above 4 hours for the high charge mode, respectively. In the calculation, harmonic cavity (499.8 MHz) and intra-beam scattering effect are considered. Next we will include more practical factors in the calculation, e.g., the impedance effects, etc.

### ID Effects

The effects of the IDs for the 14 beam lines that to be constructed in the first phase of the HEPS project are under evaluation [20].

We have developed a symplectic integrator model of the IDs in the lattice. It was found that the IDs can cause a vertical tune shift of 0.01 and a vertical beta beating of 0.3%. Nevertheless, the tunes can be restored by adjusting the strengths of two families of quadrupoles near the IDs. The horizontal emittance can be reduced to 36 pm when the IDs are included in the 60-pm lattice.

The ID error effects are also studied. It was found that at present the influence of ID integral field error can be compensated by two correctors near the ID.

### Other Studies

Beam orbit stability is essential for user experiments, a fast orbit feedback system capable to suppress orbit perturbation from DC up to 1 kHz and fewer than 10% beam sizes is under consideration. The amplitude degradation and the phase shift of the corrector magnetic field due to the eddy current effect of the vacuum chamber are studied [21]. Some preliminary calculation of the performance of the feedback system is reported in Ref. [22].

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