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SIMULATION STUDIES OF FIRST-TURN COMMISSIONING FOR THE HEPS STORAGE RING *

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Abstract

The High Energy Photon Source (HEPS) is an ultra-low emittance storage ring light source being built in Beijing, China. Due to the characteristics of the compact 7BA structure with strong focusing, achieving beam storage in the storage ring is expected to be very challenging. Our simulations confirmed the difficulty in the HEPS storage ring. This paper introduces the preparations made for the first-turn commissioning of the HEPS storage ring from the first injection to beam storage. The commissioning methods and simulation results for several key steps are discussed, including first-turns trajectory correction, RF parameters' optimization, as well as the measurement and adjustment of tune in the first turns.

INTRODUCTION

The HEPS is a 1360.4 m, 6 GeV storage ring synchrotron radiation source. The HEPS storage ring is equipped with 480 bi-directional corrector magnets and 578 beam position monitors (BPMs) for orbit corrections [1]. Based on the Accelerator Toolbox [2], we conducted commissioning simulations with various correction procedures from the first injection to beam storage, on the imperfect lattices with physical apertures and random errors in the magnets and BPMs (Table 1,Table 2, [3]), along with various injection beam errors. The BPM errors coming out from the following two data processing modes were considered: SinglePass mode and TurnByTurn (TBT) mode. The SinglePass mode uses the time-domain algorithm with a lower resolution, while the TBT mode requires the beam transmission in the storage ring for at least 20 turns and provides a higher resolution.

The starting point of the simulations is the exit of the injection Lambertson magnet (LSM). The trajectory error settings of the injected beam at this position include three different types: STD [4], RMS [5] and Offset. STD represents the six-dimensional (6D) phase space distribution of the particles in a bunch and is used for multi-particle tracking. RMS reflects the jitter of the central position of each bunch. The above two types of error settings can be found in Table 3. Offset represents the systematic deviation of the injected-beam center in the 6D phase space, which can be corrected and adjusted in subsequent processes. The analysis of Offset setting is discussed in the pre-correction section of the injection beam.

THE SIMULATION PROCESS OF FIRST-TURN COMMISSIONING

At the beginning of beam commissioning, the RF cavities, sextupole and octupole magnets are turned off, and the gaps of the IDs and collimators are opened. We assume the injected beam can move through more than 2 BPMs. In the following context, "Beam transmission XXX turns" refers to the condition that at least 10% of the initial particle can survive until the XXXth turn, which is the threshold for reliable beam data assumed in the simulations. The commissioning process consists of application of several different correction method with different beam conditions, and these correction methods will be iterated with previous corrections involved in subsequent processes.

Table 1: Magnet Misalignments and Other Errors (RMS)

	Unit	Bend	Quad	Sext	Girder
Shift X/Y	μm	200	30	30	50
Shift Z	μm	150	150	150	200
Tilt X/Y	mrad	0.2	0.2	0.2	0.1
Tilt Z	mrad	0.1	0.2	0.2	0.1
Field Error	\	3e-4	2e-4	3e-4	\

Table 2: BPM Data Errors (RMS)

BPM	Value
Offset (μm)	30
Gain	150
Rotation (mrad)	0.2
Resolution of SinglePass (μm)	0.2
Resolution of TBT (μm)	3e-4

Table 3: Injected-Beam Errors

	STD	RMS
X (mm)	0.344941	0.1
X' (mrad)	0.091443	0.03
Y (mm)	0.152882	0.1
Y' (mrad)	0.041372	0.03
Delta P	1e-3	5e-3
Delta T*C (m)	1e-2	5e-12

Pre-Correction of the Injected Beam

The subsequent correction methods in this article are all based on the beam information provided by BPM, so the beam entering the storage ring needs to have a certain transmission distance. This requires pre-correction of the offset of the injected beam.

To perform the pre-correction simulation, the beam must pass at least two BPMs. If the beam can't pass through two BPMs, it needs manual adjustment or correction through the transport line. The correction is calculated as:

$$\begin{bmatrix}\Delta X\\ \Delta X'\\ \Delta Y\\ \Delta Y'\end{bmatrix} = {RM_{Inj-traj}}^{-1} * \begin{bmatrix}X\\ Y\end{bmatrix},$$

where [X Y]' represents the SinglePass data of the beam passing through the BPM, $RM_{Inj-traj}$ is the theoretical response matrix between the injected beam coordinate and the first-turn trajectory, and $[\Delta X, \Delta X', \Delta Y, \Delta Y']'$is the correction value of beam coordinate at the exit of the LSM

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magnet. In the simulation, 10000 macroparticles were firstly generated randomly and tracked. Based on the tracking results, 1000 macroparticles, which can pass through two BPMs, were selected for correction simulations. The RMS values of the corrected 4D coordinate has an STD value of [0.1505 mm, 0.6169 mrad, 0.1393 mm, 0.06126 mrad], which is set as the offset of the injection beam in the correction simulation (Fig. 1).

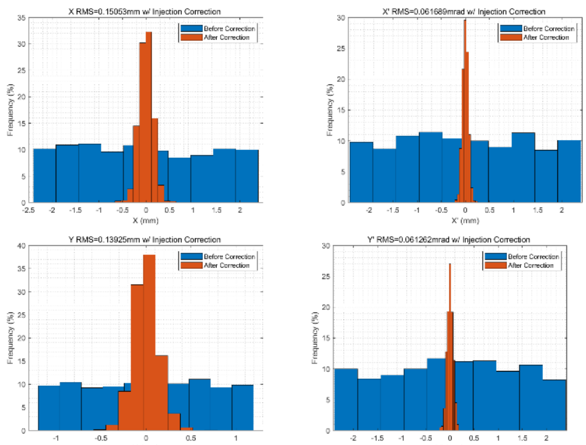

Figure 1: Change of 4D coordinates of the beam before and after the preliminary correction of the injection beam. Blue: Before correction. Red: After correction.

First-Turn Correction

The first-turn trajectory correction is to optimize the beam trajectory by adjusting the corrector strengths, in order to make the beam survive more turns. The correction used the response matrix between the beam trajectory and the corrector strength, based on the calculation for the ideal lattice. The process is iterated, combining newly obtained BPM data with the same method, until multiple-turn beam trajectories are obtained. In the simulation, the first-turn trajectory correction aims for the beam survival of more than 5 turns. Figure 2 shows the result of one of the simulated corrections: after 15 iterations, the beam reaches the 7th turn with an RMS trajectory about 1.5 mm/0.6 mm for horizontal and vertical at BPMs, and around 0.6 mm/0.3 mm for the first turn.

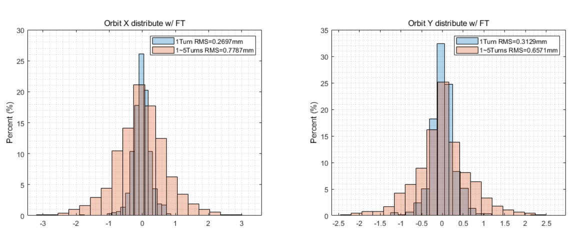

Figure 2: Beam trajectory distribution at BPMs after first turn correction (FT), left for horizontal and right for vertical.

After obtaining the beam trajectories for more than five turns, the beam energy variation is characterized by the average of the horizontal trajectories <x> of each BPM in each turn. Figure 3 shows the effect of switching on/off the RF cavities on the beam's average horizontal trajectory after the first-turn trajectory correction. Beam loss is due to synchrotron radiation-induced energy loss before the cavities are turned on. Three 499.8 MHz RF cavities were turned on with 1.3 MV peak voltage for each cavity, and the RF frequency and phase were manually scanned. The simulation results show the beam can be transmitted for about 30 turns after the RF cavities are turned on (Fig. 3, right).

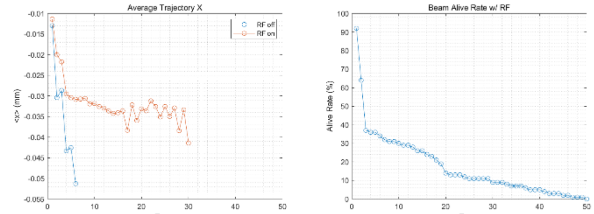

Figure 3: Left: Variation of the horizontal average trajectory per turn, blue: RF off; red: RF on. Right: Beam survival rate after turning on the RF cavities, with the beam transmission around 30 turns.

Multi-Turns Correction

The average of multi-turn beam trajectory can serve as an approximation of the closed orbit, which we will refer to as the "approximate closed orbit" below. The correction method used is similar to closed orbit correction, and in the simulations, we used a response matrix derived from the ideal lattice with only a small fraction of singular values, about 20%. After several iterations, over 10% of the beam was transported for over 500 turns as shown in Fig. 4 left, and the RMS values of the horizontal and vertical approximate closed orbits were reduced to around 200um (Fig. 4Figure 4, right), mainly limited by the BPM offset.

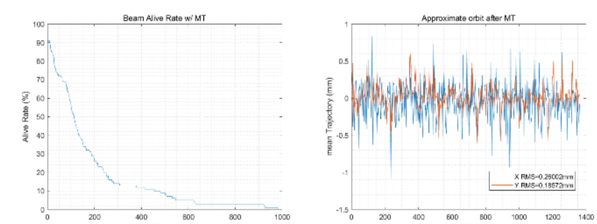

Figure 4: Left: Beam survival rate after the multi-turn trajectory correction, where the beam transmission exceeds 500 turns. Right: Approximate closed orbit after multi-turn trajectory correction, blue: horizontal direction with ~ 0.26 mm rms; red: vertical direction with ~ 0.19 mm rms.

Correction of Injection Beam

The initial oscillation amplitudes of the beam center is too large and could cause beam loss. To solve this problem, a correction to the injection beam coordinates was introduced during the multi-turn trajectory iteration process. The first-turn trajectory was adjusted by calculating the coordinates at the exit of the LMS to approach the approximate closed orbit and refined through the transport line. This correction method was used after obtaining a beam with more than 20 turns, and reduced the residual oscillation of the beam by around 50%. Figures 5 and 6 show the results of one simulated correction. After correction, the

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oscillation amplitude of the beam at each BPM in the first ten turns is roughly reduced to 50% of that before correction. The survival rate of the beam within 50 turns before and after correction increased from 73% to 84%.

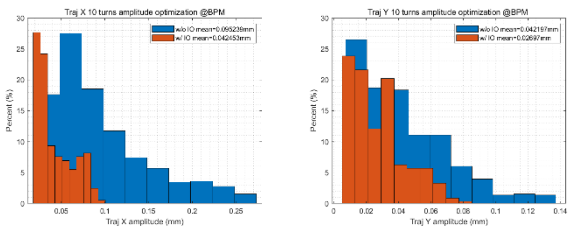

Figure 5: Beam oscillation changes in the first 10 turns before and after correction of injection beam coordinates, left: horizontal; right: vertical. Blue: before correction; red: after correction.

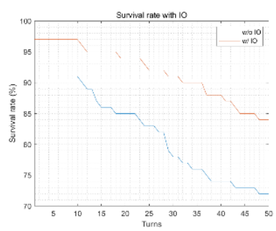

Figure 6: Beam survival rate within first 50 turns before and after the correction of injected beam.

Longitudinal Parameter Calibration

After the corrections mentioned above, additional adjustments are required to reduce the longitudinal oscillations and phase shifts in the beam. The primary adjustments involve the injected beam delay (RF phase), RF frequency, and injected beam center energy.

The correction method [6] involves scanning the RF cavity phase within ±π, recording the slope of the average horizontal trajectory <x> for the first 25 turns at each phase, fitting the relationship between the synchronous phase and the slope of <x> change using a zero-crossing sine function, and using the zero-crossing point of the fitting function as the phase adjustment target.

The RF frequency can be knobbed manually to minimize the amplitude of the mean value of the approximate closed orbit. In addition, we also reduced the energy deviation of the injected beam, the goal is to match the first 10 turns' <x> with the average of the horizontal closed orbit after the beam stabilizes (100-400 turns). The method is:

1. Scan the injected beam energy.
2. Record Δ<x>, the difference between the first 10 turns' horizontal closed orbit average and turns 100-400 average.
3. Linearly fit the injected beam energy and Δ<x> and find the zero-crossing point to determine the adjustment amount.

Figure 7 displays the effectiveness of longitudinal parameter corrections. The left graph presents the adjustment curve for phase correction, while the right graph illustrates the reduction of <x> oscillation after the correction of the injected beam energy. As a result of these corrections, the amplitude of the beam oscillation is significantly reduced, and the beam transmission can exceed 1000 turns.

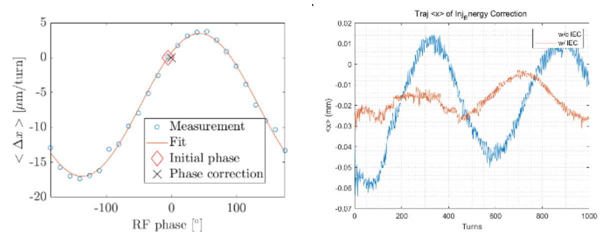

Figure 7: Left: Curve obtained by fitting during phase correction and the phase change before (Initial Phase) and after (Phase Correction) correction. Right: Changes in the oscillation of average injection beam trajectory <x> before and after the correction of the injected beam energy. The blue and red curves represent the result before correction, and the result after correction, respectively.

Ramp-up of Sextupole Magnet

To ramp up the sextupole magnet, the working point shift due to the feed-down effect must be measured and corrected. The Phased-CFT [7] and MIA [8] methods are used to measure the decimal and integer parts of the working point, respectively. A set of QF and QD magnets are selected to correct the working points. The sextupole magnet strengths are increased step-by-step, and trajectory and working point correction are performed after each step. The sextupole magnet strengths are finely tuned to ensure the measured chromaticity being between 0 and 5. The simulation results show that the completed ramping process of higher-order magnets allows for closed orbit and optics correction based on TBT. The beam can survive for more than 10,000 turns with a survival rate of over 30% at 10,000 turns. Most beam losses occur within the first 1000 turns, after which the beam oscillations are damped, and no further beam loss is observed. Figure 8 shows the beam survival rate after the ramping process.

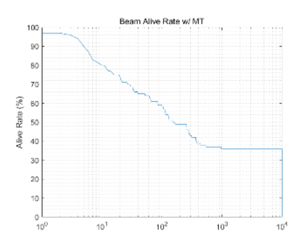

Figure 8: Beam survival rate after sextupole magnet ramp-up.

CONCLUSIONS

This article discusses the simulations of the first-turn beam commissioning for the HEPS storage ring, which includes the main process of corrections with the consideration of machine errors. The next step is to study methods for detecting abnormal situations which may happen during the commissioning process, which will be more complicated.

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