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THE BEAM-BASED ALIGNMENT SIMULATION AND PRELIMINARY EXPERIMENT AT SXFEL

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Abstract

The Shanghai soft X-ray Free-electron Laser facility (SXFEL) is now serving as an experimental platform for fundamental free-electron laser (FEL) principal tests. This facility puts very tight tolerances on the straightness of the electron beam trajectory (within 5 µm). It is hard to achieve the required orbit due to the off-axis fields of the misaligned quadrupoles and undulator segments especially for the SXFEL driven by relatively low energy LINAC (840 MeV). The tight tolerances can be met through beam-based alignment (BBA) technique. In this paper, the BBA simulation and preliminary experiment results at SXFEL are presented. To further improve the electron beam trajectory by calculating the undulator misalignment, the feasibility of genetic algorithm (GA) based BBA has been studied.

INTRODUCTION

Shanghai soft X-ray Free-electron Laser facility (SXFEL) finished civil construction and equipment installation by the end of 2016. It is now under commissioning and serves as an experimental platform for fundamental FEL study [1]. The main parameters of SXFEL are listed in Table 1.

Table 1: Main Parameters of the SXFEL [2]

Parameters	Value	Unit
Beam energy	840	Mev
Normalized emittance(rms)	≤1.5	mm·mrad
Bunch charge	500	pC
Slice energy spread	30	keV
Peak current	500	A
Electron bunch length	1	ps
Seed wavelength	265	nm
FEL wavelength	8.8	nm
Undulator length	126×2.35	cm

The deviation of electron beam with respect to the desired orbit is required to be within several microns [3]. This trajectory can be achieved by the beam-based alignment (BBA) technique [4] which was proposed in 1980s.

Although the state-of-the-art BBA technique has achieved great success at LCLS [5] [6], European-FEL [7], SACLA [8], PAL-XFEL [9, 10] with relatively high electron beam energies, there is no report about satisfactory BBA experiment on soft X-ray FEL facilities driven by relatively low energy linacs (on the order of 2 GeV or less) up to now. This predicament in soft X-ray FEL is blamed on the ignorance of undulator misalignment which gives rise to the outrageous perturbation of electron beam trajectory [11]. To solve this problem, the genetic algorithm (GA) is introduced and simulations based on the SXFEL are carried out.

BBA SIMULATION

Dispersion-free Steering

The most successful BBA technique is the dispersion-free steering (DFS) method which is implemented using large electron energy variations and sub-micron resolution beam position monitors (BPMs). The readback of the ith BPM, m_i, at location s_i along the undulator can be written as Eq. (1).

$$\begin{aligned} m_i &= \xi_i - b_i + x_0 R_{11}(s_0, s_i) + x_0' R_{12}(s_0, s_i) \\ &+ \sum_{j}^{Nc} \theta_j R_{12}(s_j, s_i) + \sum_{j=1}^{Nq} d_j M_{ij} \end{aligned} \tag{1}$$

where ξ_i denotes a stochastic variable representing the ith BPM precision error, b_i denotes the ith BPM offset, θ_j denotes the kick angle of the jth dipole corrector which located at s_j, x_0 and x_0' are the transverse launch position and angle of the electron beam, the coefficients R_{11} and R_{12} are the elements of the corresponding transport matrix, Nc and Nq denotes the number of correctors and quadrupoles, M_{ij} relates d_j, the jth quadrupole transverse mislignments, to a position offset at ith BPM which is specifically shown as Eq. (2)

$$\begin{aligned} M_{ij} &= R_{11}(s_i, s_j)(1 - cos(\sqrt{K}L)) \\ &+ R_{12}(s_i, s_j)\sqrt{K} sin(\sqrt{K}L) \end{aligned} \tag{2}$$

K and L are the normalized strength and effective length of the jth quadrupole, respectively.

Once enough BPM readings has been obtained, the electron beam launch condition, the quadrupole position and the BPM offsets can be derived by using the singular-value decomposition (SVD).

Simulation Results

The simulation has been performed for the long radiator of the second section (R2) which is comprised of 6 tunable undulator segments. The entire BBA simulation has been

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Table 2: List of Errors Used in the BBA Simulation

Errors (Gaussian rms errors)	Value	Unit
Quadrupole rms misalignment	50	µm
BPM rms misalignment	50	µm
BPM rms resolution (multi-pulse)	0.1	µm
Launch position rms variation	30	µm
Launch angle rms variation	30	µrad

accomplished based on the parameters shown in Table 1. The errors used in the simulation are listed in Table 2.

Figure 1 shows the initial quadrupole misalignment, BPM offsets and electron beam trajectories in horizontal and vertical directions at 840 MeV, 730 MeV, 610 MeV. The horizontal rms electron beam orbits are about 124 µm, 110 µm and 98 µm for beam energy 610 MeV, 730 MeV and 840 MeV, respectively. The vertical rms electron beam orbit do about 150 µm, 145 µm and 130 µm, respectively.

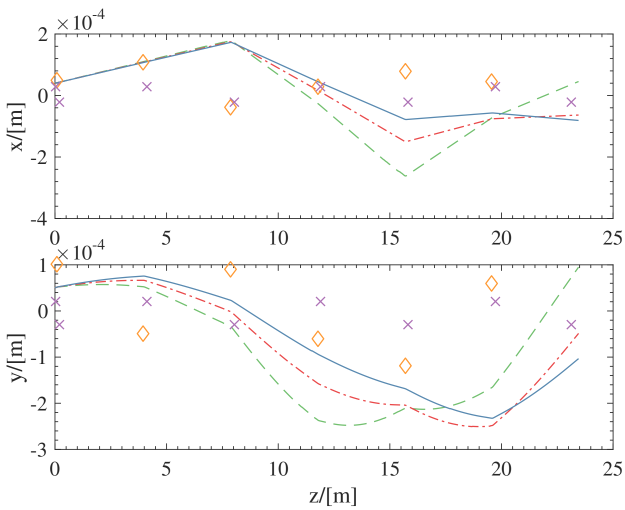

Figure 1: The initial horizontal (up) and vertical (down) quadrupole misalignment (orange-diamond), BPM offsets (purple-cross), electron orbit at 840 MeV (blue), 730 MeV (red), 610 MeV (green).

The misalignment of quadrupoles and BPMs are calculated and corrected by the method of DFS. After several iterations, the electron beam orbit and positions of quadrupoles and BPMs are shown in Fig. 2. The residual misalignment of quadrupoles and BPMs are about several microns and the rms electron beam trajectories at 840 MeV are 1.1 µm and 1.7 µm in the horizontal and vertical planes.

The simulation results show that the rms electron beam trajectories are improved from 10^{-4}m to 10^{-6}m for each beam energy in both planes. It indicates an efficient overlap between the electron beam and the radiation which guarantees a significant increase of FEL power.

PRELIMINARY BBA EXPERIMENT

Due to the electron beam quality, only half of the R2 section was involved in the experiment. Without the consideration of the launch position and angle, the procedure of BBA experiment is given as follows:

- Roughly correct the beam trajectory at 610 MeV using upstream correctors so that the electron beam passes through all the undulators.
- Move the quadrupoles mounted on the motorized 2D movers one by one and record the BPM readings for each of 610 MeV, 730 MeV and 840 MeV.
- Analysis the BPM data through the DFS method.
- Set quadrupole movers and correct BPM offset based on last step calculation.
- Repeat steps 2 ~ 4 for several times until the calculated corrections at 840 MeV is less than 5 µm.

After carefully tuning the linac at 610 MeV, the beam launch condition was recorded. Every time the energy was switched, this launch condition should be unchanged by scaling up the strength of all magnets according to the energies.

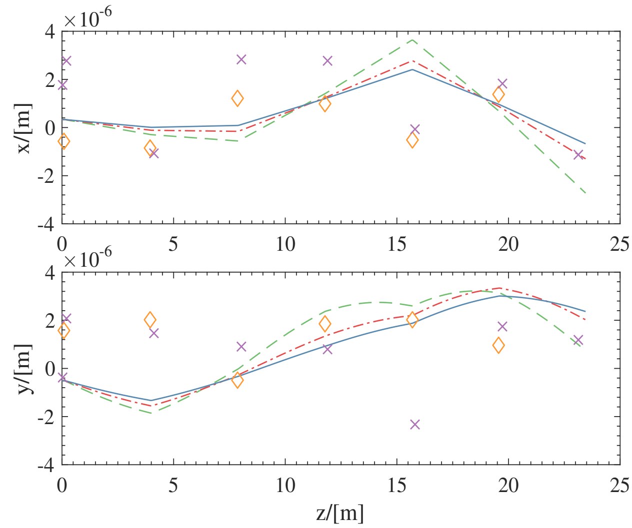

Figure 2: The position of quadrupoles (orange-diamond) and BPMs (purple-cross), the electron beam trajectories at 840 MeV (blue), 730 MeV (red), 610 MeV (green) after correction in the horizontal (up) and vertical (down) planes.

Figure 3 illustrates the response matrix at different energies in both directions. The evolution of the electron beam trajectories is shown in Fig. 4. The rms electron beam orbits over the length of selected radiator section are improved from 1.22 mm to 87.2 µm in the horizontal planes and from 1.26 mm to 75.9 µm in the vertical planes.

Although the trajectories have been improved a lot, they are still far from the requirement [3].This may result mainly from the electron beam sensitivity to the misalignment of quadrupoles and undulator segments, especially for the low-energy electron beam at SXFEL. The undulator misalignment, unfortunately, can not be calculated by the DFS method. But nevertheless, this preliminary BBA experiment is expected to be beneficial for the future BBA experiment.

BBA WITH GENETIC ALGORITHM

For further optimization, a feasible method combining the BBA with GA [12] is proposed to calculate the quadrupole

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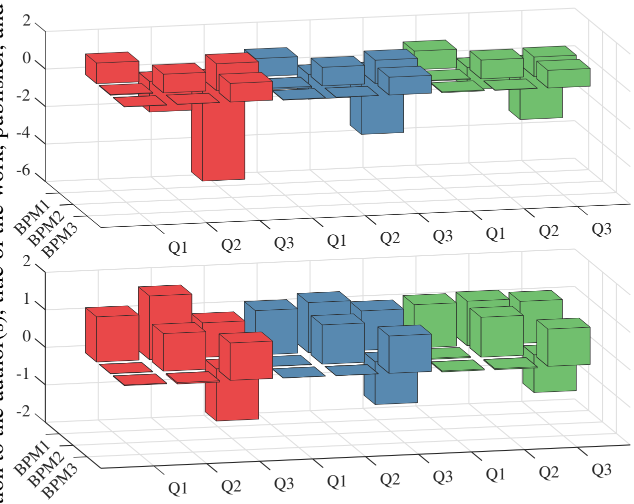

Figure 3: The response matrix for 840 MeV (red), 730 MeV (blue) and 610 MeV (green) in horizontal (up) and vertical (down) directions.

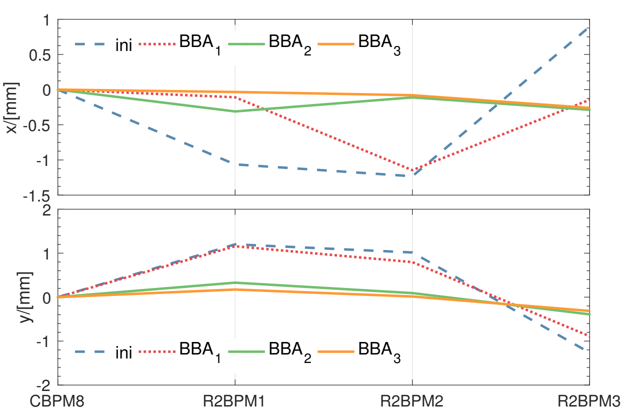

Figure 4: The initial beam trajectories (blue) and orbits after 1^{st} (red), 2^{nd} (green) and 3^{th} (orange) iteration of BBA procedure in the horizontal (up) and vertical (down) planes.

positions and BPM offsets in both directions and undulator misalignment (transverse offset and tilt) in the vertical plane. [11]

The GA becomes convergent after tens of generations. The residual misalignment for each specific accelerator component in horizontal and vertical directions is demonstrated in Fig. 5. The residual misalignment is smaller than 1 µm.

With the results in Fig. 5, the electron beam trajectories before and after GA-based BBA in the horizontal and vertical plane are exhibited in Fig. 6. The result indicates a significant improvement of the electron beam trajectories. By adopting the proposed method, the rms electron beam orbits are about 0.12µm in horizontal plane and 0.10 µm in vertical plane. For comparison, the electron beam trajectories after DFS method are also included.

A satisfactory result has been obtained by means of GA-based BBA.It might be an alternative BBA experimental protocol at SXFEL since the undulator misalignment can be derived.

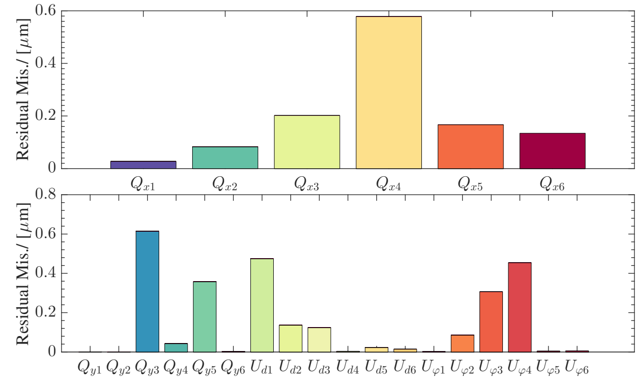

Figure 5: The residual misalignment for each component in horizontal (up) and vertical (down) directions. (Q, U_d and U_φ denotes the quadrupole offsets, undulator transverse offsets and undulator tilts in the corresponding plane)

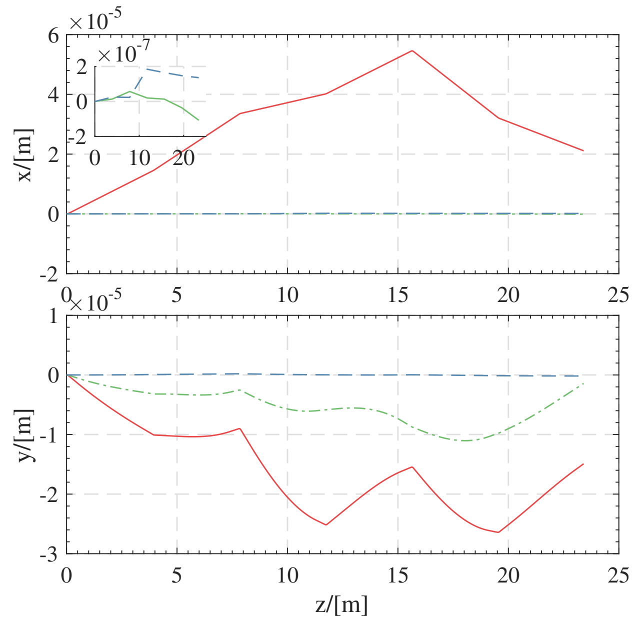

Figure 6: The electron beam orbit before (red) and after (blue) GA-based BBA, after DFS (green) method in the horizontal (up) and vertical (down) planes.

SUMMARY

In this paper, we demonstrated a BBA simulation based on the SXFEL radiator section and the result of a preliminary BBA experiment. The experiment result shows an improvement of the electron beam trajectories in horizontal and vertical directions. For further optimization, the genetic algorithm has been introduced to obtain the misalignment of the undulator segments. Although more efforts are still needed, this BBA study is expected to be useful to the SHINE [13] BBA experiment.

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