Beam-based alignment in the European XFEL SASE1

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Abstract

The European X-ray Free Electron Laser (E-XFEL) provides an ultra-short and high-brilliant photon pulses of spatially coherent X-rays with wavelengths down to 0.5 Å by using three undulator systems. Within these undulator systems, the orbit trajectory is required to be straight to a few micron over each gain length, so that the photon beam is capable of overlapping efficiently with the electron beam. However, this requirement is not obtainable with ordinary mechanical alignment methods. For this reason, a beam-based alignment (BBA) method using BPM readings of different beam energies is applied to the E-XFEL SASE1 undulators. In this report, we describe the BBA simulation for SASE1 including alignment errors of quadrupoles and BPMs. After correction, the desired range of the orbit trajectory is attained with high confidence. In addition, to identify the reliability of an aligned orbit trajectory acquired from the BBA simulation, we present here the SASE FEL radiation simulation, in which we observe a slight decrease of radiation energy and power.

I. INTRODUCTION

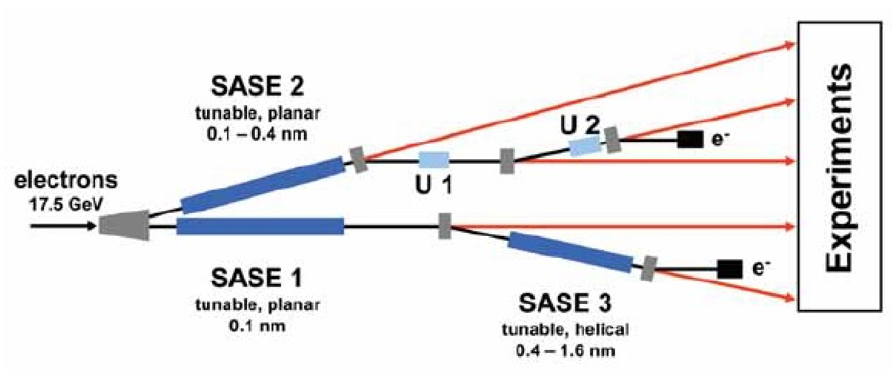

FIG. 1. Schematic view of the E-XFEL undulator systems.

The European X-ray Free Electron Laser (E-XFEL) [1] is a fourth-generation light source with high beam energy up to 20 GeV (17.5 GeV ia a beam energy for the standard operation mode). There are three undulator systems in the E-XFEL to produce hard and soft X-ray pulses using the process of self-amplified spontaneous emission (SASE). In the E-XFEL undulators, one branch serves SASE1 and SASE3, and the other one serves only SASE2. SASE1 and SASE2 are optimized for the hard x-ray radiation ranged from 4 to 29.2 keV. The schematic view of E-XFEL undulator systems is shown in Fig. 1. In both SASE1 and SASE2, there are 35 undulator cells and each undulator cell consists of a 5-m-long undulator segment and 1.1-m-long intersection as shown in Fig. 2. Additionally, in the undulator cells, every undulator segment is made of 250 permanent dipole magnets and every intersection is composed of a high-resolution beam position monitor (BPM) and quadrupole magnet which is transversely controlled by a mechanical mover.

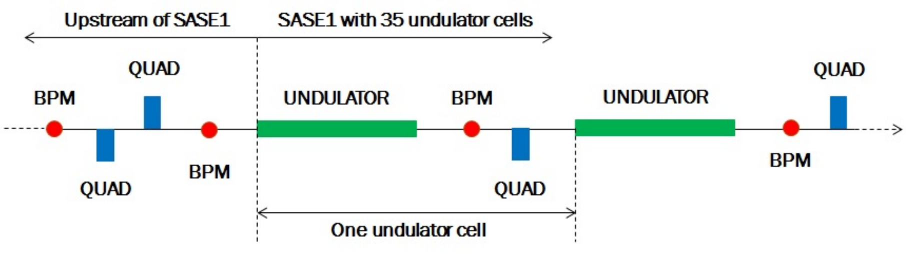

FIG. 2. Schematic view of the E-XFEL SASE1 undulators. SASE2 has same structure with SASE1.

The deviation of the electrons with respect to the design trajectory is required to be strongly regulated in the undulators, generally within a few μm. This regulation can be achieved by using the beam-based alignment (BBA) method, which uses BPM readings of different beam energies. In general, the BPM reading is shifted by a misalignment of the BPM and this shift is independent of beam energy. On the other hand, a misalignment of quadrupole distorts the downstream orbit trajectory, depending on beam energy. As a result, the unknown misalignments of quadrupoles and BPMs can be found with BPM readings of various beam energies. This BBA method has been established at the LCLS [2] and successfully performed, after which the rms orbit trajectory achieved a value of 3 μm. In this report, we apply this BBA method to the E-XFEL SASE1 undulators.

The distorted orbit trajectory deteriorates the SASE FEL radiation process [3] in an undulator. Therefore, the reliability of the orbit trajectory obtained by the BBA method can be identified through the simulation of the SASE FEL radiation process. Before simulating the SASE FEL radiation process, start-to-end numerical simulations are carried out from the photo-cathode gun to the entrance of an undulator. Using the particle tracking codes, *ASTRA* [4] and *ELEGANT* [5], space charge effect and cavity wakefield are taken into account through the accelerator and the coherent synchrotron radiation effect is included in the bunch compressor. The SASE FEL radiation process is analyzed by the three-dimensional, time-dependent FEL code, *GENESIS 1.3* [6] using the output distribution of *ELEGANT*. The radiation energy and power induced by the aligned orbit trajectories are compared with those induced by a straight orbit trajectory.

II. BBA ANALYSIS

The BPM measures the transverse position of the electron beam, and the BPM reading x_i at an ith BPM can be written as [7]

$$x_i = \sum_{j=1}^{i} M_{ij}\theta_j + L_{i1}x_0 + L_{i2}x_0' - \beta_i + \xi_i, \tag{1}$$

where M_{ij} is the coefficient of transfer matrix from the point j to i, θ_j is the transverse kick angle at the point $j(< i)$ caused by the misalignment of a quadrupole which is located at the upstream of ith BPM, L is the launch response matrix, x_0 and x_0' are the initial launch position and angle, respectively, β_i is the misalignment of the ith BPM, and ξ is the BPM resolution error. In this equation, the kick angle θ is inversely proportional to the beam energy, but the BPM misalignment β is independent of the beam energy. The transfer coefficient M_{ij} is depending upon the beam energy. The orbit trajectory with respect to a straight line is given by $x + \beta$. The matrix expression of Eq. 1 for one beam energy is given as

$$\begin{pmatrix} x_1 \\ \vdots \\ x_N \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ \vdots & \vdots \\ L_{N1} & L_{N2} \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} + \begin{pmatrix} R_{11} & \ldots & R_{1M} \\ \vdots & \ddots & \vdots \\ R_{N1} & \ldots & R_{NM} \end{pmatrix} \begin{pmatrix} d_1 \\ \vdots \\ d_M \end{pmatrix} + \begin{pmatrix} & & \\ & -I & \\ & & \end{pmatrix} \begin{pmatrix} \beta_1 \\ \vdots \\ \beta_N \end{pmatrix} + \begin{pmatrix} \xi_1 \\ \vdots \\ \xi_N \end{pmatrix}, \tag{2}$$

where M and N are the number of quadrupoles and BPMs, respectively, R is the orbit response matrix, d is the quadrupole misalignment, and I is an $N \times N$ unit matrix.

To identify the unknown parameters, the initial launch condition and misalignments of quadrupoles and BPMs, the minimum number of beam energies has to be verified. The number of unknown parameters, N_U, corresponding to N BPMs, M quadrupoles, and 2 launch parameters of N_E beam energies is given by

$$N_U = N + M + 2N_E - 2. \tag{3}$$

Here are the 2 arbitrary reference line parameters subtracted. On the other hand, the total number of BPM readings, N_B, is

$$N_B = N \cdot N_E. \tag{4}$$

To find the unknown parameters N_U, the N_B has to be larger than N_U. Accordingly, the minimum number of beam energies is given by

$$N_E \geq \frac{N + M - 2}{N - 2}. \tag{5}$$

For the E-XFEL SASE1 undulators, at least three beam energies are needed. Therefore, beam energies, 8.0, 14.0, and 17.5 GeV, are selected within the E-XFEL operation modes in the following BBA simulations.

III. BBA PROCEDURE

The BBA procedure which is used in simulations is shown in Table I. At first the launch and orbit response matrices are obtained for all energies. Secondly, the BPM readings of three beam energies are obtained after errors are applied. Thirdly, quadrupole and BPM misalignments are calculated by using SVD method from Eq. 2. Fourthly, quadrupoles are adjusted to new positions and BPM misalignments are corrected with calculated values. Fifthly, the launch position and angle are corrected with the linear fit of calculated misalignments. Sixthly, the BPM readings are steered to remove remaining small oscillations, using the minimum number of quadrupole movers. Finally, steps 2–6 are repeated until the decrease of the rms orbit trajectory saturates.

Step	Description
1	Obtain launch and orbit response matrices for all beam energies
2	Collect BPM readings disturbed by quadrupole and BPM errors
3	Analyze BPM readings and calculate errors
4	Adjust quadrupole and BPM errors using the result of step 3
5	Correct launch condition
6	Remove remaining small oscillations with minimum number of quadrupole movers
7	Repeat steps 2-6 until the decrease of rms orbit trajectory saturates

TABLE I. Beam-based alignment procedure

IV. BBA SIMULATIONS

The BBA simulation has been accomplished with a simulation code, *ELEGANT* as the above procedure. The statistical and systematic errors of quadrupoles and BPMs are taken into consideration in the simulation, and the initial beam position and angle are considered as a static launch error which is larger than the rms beam size in horizontal and vertical planes. These errors are listed in Table II.

Errors (Gaussian rms)	Value	Unit
Quad. rms misalignment	300	μm
BPM rms misalignment	300	μm
BPM rms resolution	1	μm
Launch position rms variation	100	μm
Launch angle rms variation	100	μrad

TABLE II. List of errors used in simulations. Each error has a gaussian distribution.

Figure 3 shows the transverse misalignments of quadrupoles and BPMs used in the simulation regarding a straight line. The misalignments of quadrupoles and BPMs are individually generated with one random seed. The BPM resolution error is not included here.

Figure 4 shows the horizontal and vertical orbit trajectories, which are disturbed by the errors of quadrupoles and BPMs, through the undulators for three beam energies. These orbit trajectories are given from the BPM readings, which are practically the only known quantities, after being shifted by the misalignments of BPMs. The initial launch position and angle are separately applied to each beam energy. As a result, the horizontal rms orbit trajectories increase to about 2.2, 2.0,

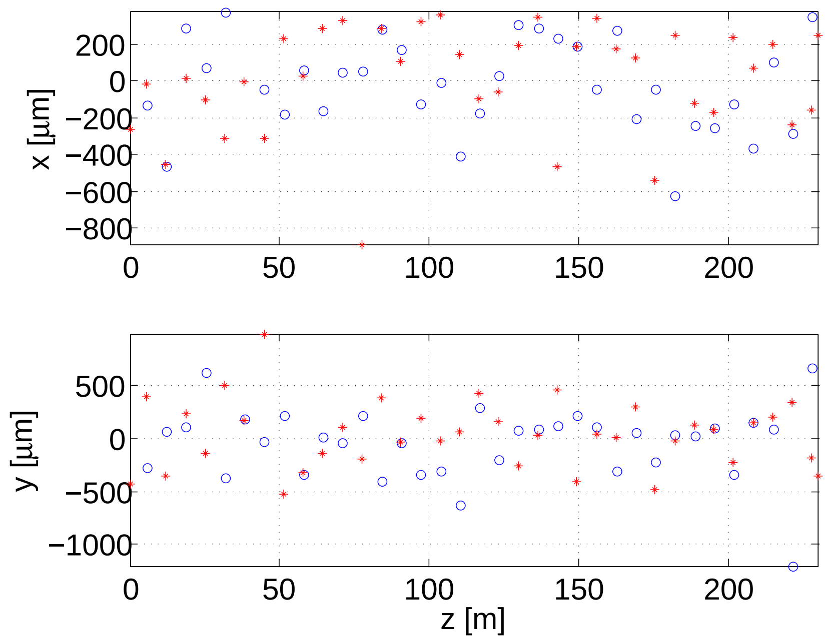

FIG. 3. Misalignments of quadrupoles (blue-circle) and BPMs (red-asterisk) in horizontal (up) and vertical (down) planes along the undulator length for one random seed.

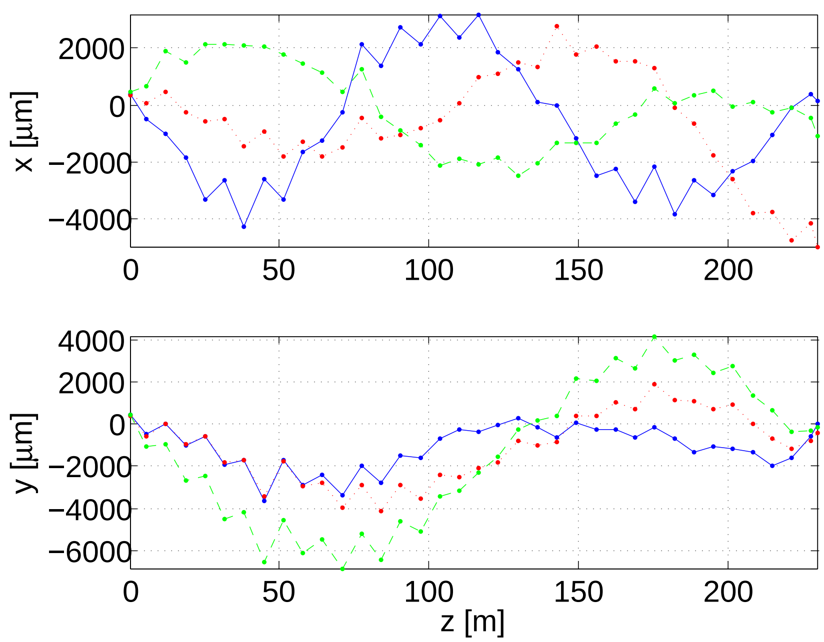

FIG. 4. Horizontal (up) and vertical (down) orbit trajectories of three beam energies, 8.0 (blue), 14.0 (red), and 17.5 (green) GeV with quadrupole and BPM errors.

and 1.4 mm for beam energies, 8.0, 14.0, and 17.5 GeV, respectively, and the vertical rms orbit trajectories do about 1.5, 1.9, and 3.5 mm, respectively.

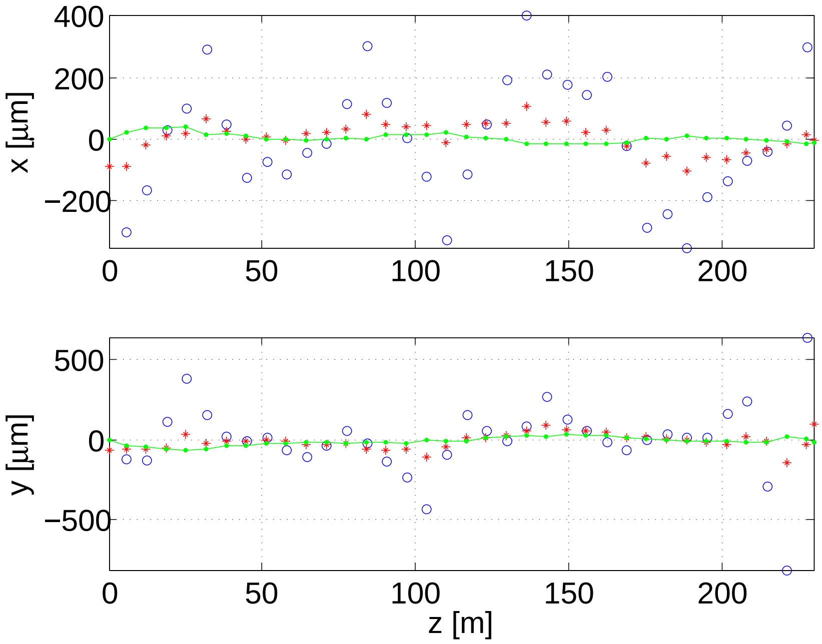

FIG. 5. Orbit trajectories(green-line), quadrupole positions(blue-circle), and BPM readings(red-asterisk) in horizontal (up) and vertical (down) directions after first iteration at 17.5 GeV. Linear term is removed for clarity

The misalignments of quadrupoles and BPMs and launch conditions are calculated and corrected with the BPM readings of three beam energies. Figure 5 shows the quadrupole positions (blue-circle), BPM readings (red-cross), and orbit trajectories (green-line) in the horizontal and vertical planes after a first iteration of steps 2–6 at the beam energy, 17.5 GeV. The calculated misalignments of quadrupoles and BPMs have the linear term, but this linear term is removed in order to clearly show the improved straightness of the trajectories in this plot. In the horizontal plane, the rms value of quadrupole positions is about 190 μm, the rms BPM reading is about 51 μm, and the rms orbit trajectory is about 16 μm over the undulator length with respect to a straight line. In the vertical plane, those values are about 231, 52, and 26 μm, respectively. Consequently, these values are significantly improved after the first iteration of steps 2–6. Especially, the rms orbit trajectories decrease noticeably from 1–3 mm to 10–30 μm in both planes. Moreover, the launch condition is also improved through the step 5, with the decrease of about ten times compared with the initial launch condition.

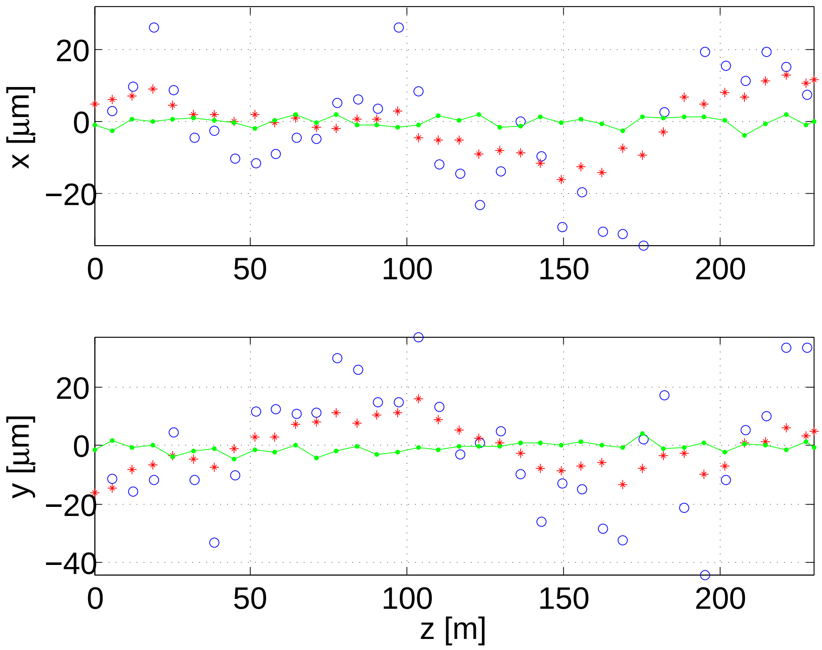

FIG. 6. Orbit trajectories(green-line), quadrupole positions(blue-circle), and BPM readings(red-asterisk) in horizontal (up) and vertical (down) directions after third iteration at 17.5 GeV.

Figure 6 shows the trajectories after a third iteration. The linear term is also gotten rid of for clarity. In the horizontal plane, the rms value of quadrupole positions is about 17 μm, the rms BPM reading is about 7.7 μm, and the rms orbit trajectory is about 1.4 μm over the undulator length, regarding a straight line. In the vertical plane, those values are about 20, 7.9, and 1.8 μm, respectively. These results are consistent with other two beam energies, so that the rms orbit trajectories achieves about 1-3 μm for each energy in both planes.

More simulations are executed with more random seeds. Figure 7 shows the average transverse orbit trajectories after the third iteration for three beam energies. The orbit trajectories are averaged after the conversion to absolute values with 100 random seeds. The horizontal rms values of average orbit trajectories are about 1.4, 1.3, and 1.4 μm for beam energies, 8.0, 14.0, and 17.5 GeV, respectively. Also the vertical rms of averaged orbit trajectories are about 1–2 μm for each beam energy. For more than 100 random seeds, they show similar results about rms orbit trajectories.

The sensitivity of the final rms orbit trajectories to the BPM resolution error is investigated as shown in Fig. 8 at the beam energy 17.5 GeV. From the Fig. 8, the increased BPM resolution error has a significant influence on the rms orbit trajectories. However these trajectories are less than 5 μm until the rms values of BPM resolution error is up to 3 μm in both planes.

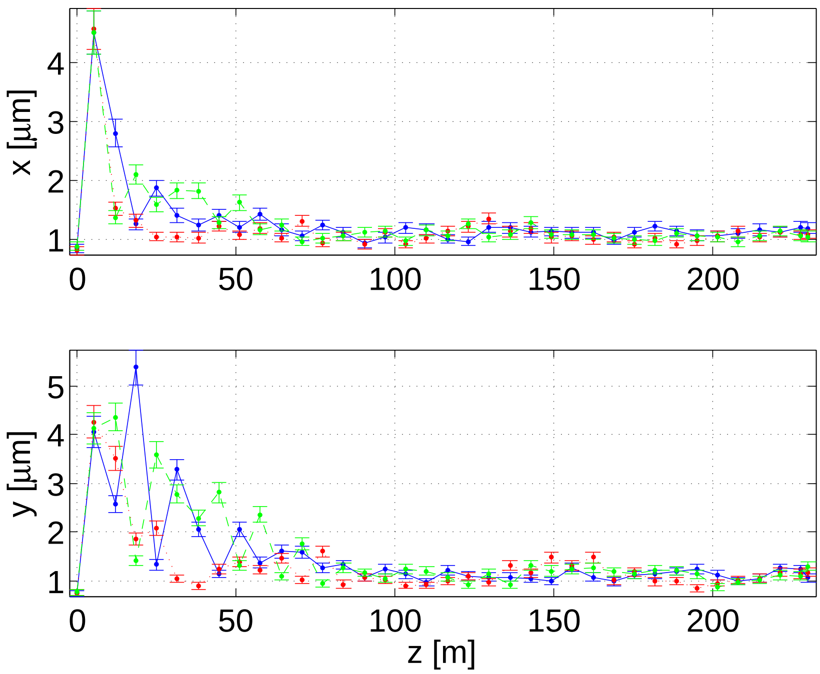

FIG. 7. Average orbit size with 100 random seeds after third iteration for three beam energies, 8.0 (blue), 14.0 (red), and 17.5 (green) GeV. Error bars represent the standard error of the mean averaging the orbit trajectories of 100 random seeds.

V. SASE FEL SIMULATIONS

The reliability of the corrected orbit trajectory after the full BBA procedure is investigated with the SASE FEL radiation process in the undulators. The *ASTRA* simulation is carried out from the photo-cathode gun to the end of the ACC1 cavity using 2×10^5 macro-particles and this output distribution of *ASTRA* passes through the rest part of the E-XFEL to the entrance of the SASE1 undulators by using the *ELEGANT* code. In these simulations, the beam charge, 1 nC, is used and beam energy reaches 17.5 GeV after the main linac. A longitudinal phase space and beam profile before entering the SASE1 undulators is shown in Fig. 9. A beam current, horizontal and vertical slice emittances, and slice energy spread are presented in the beam profile. After *ASTRA* and *ELEGANT* simulations, the peak current reaches 5 kA after a full compression through three bunch compressors, transverse slice emittances are less than 1 μm at the beam center in both planes and slice energy spread is also less than 0.2 MeV at the beam center.

Figure 10 shows the average radiation energy along the undulator length and the average radiation power along the bunch length. In this simulation, the electron beam passes through the undulators in a straight line. The radiation energy is averaged for 7310 bunch slices along the

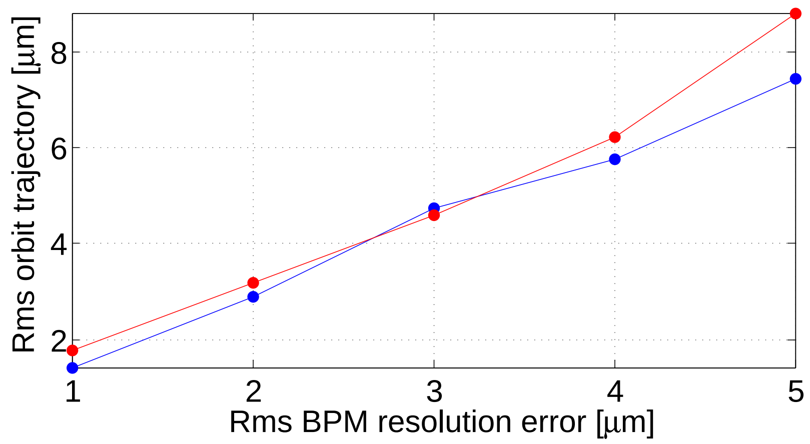

FIG. 8. Horizontal (blue) and vertical (red) rms orbit trajectories with different rms BPM resolution errors at 17.5 GeV.

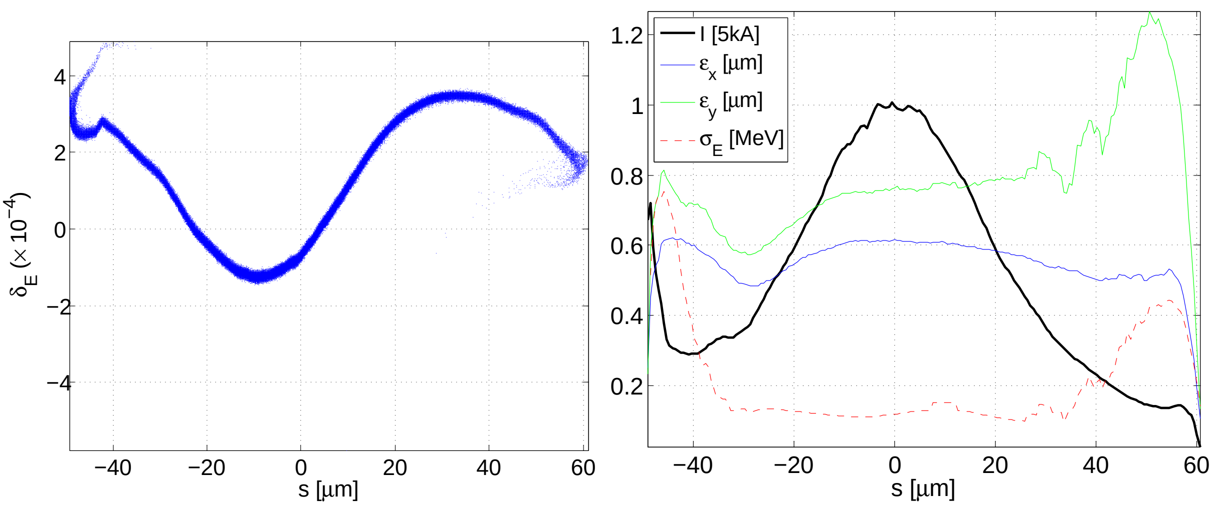

FIG. 9. Longitudinal phase space (left) and beam profile (right) before SASE1 undulators. In a beam profile figure, beam current I (black-line), horizontal (blue-line) and vertical (green-line) slice emittances $\epsilon_{x,y}$, and slice energy spread σ_E (red-dashed-line) are shown. A bunch head is on the right side. A beam charge is 1 nC and beam energy is 17.5 GeV.

undulator length and the radiation power is averaged for the total undulator length at each slice. The saturation of the average radiation energy appears at around 121 m along the undulator length. The peak values of the average radiation energy and power are about 5.7 mJ and 24 GW, respectively. These results are compared with ones of orbit trajectories aligned by the BBA procedure.

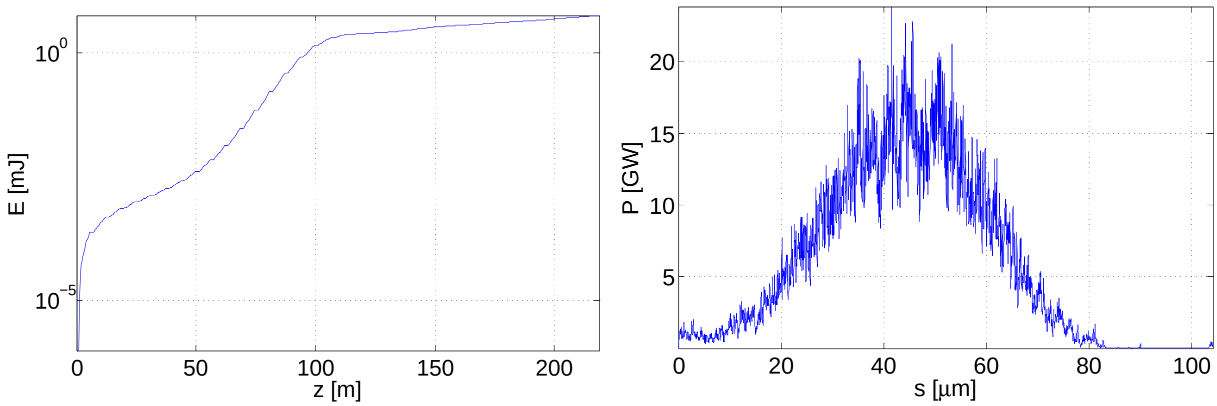

FIG. 10. Average radiation energy along the undulator length (left) and average radiation power along the bunch length (right) without errors.

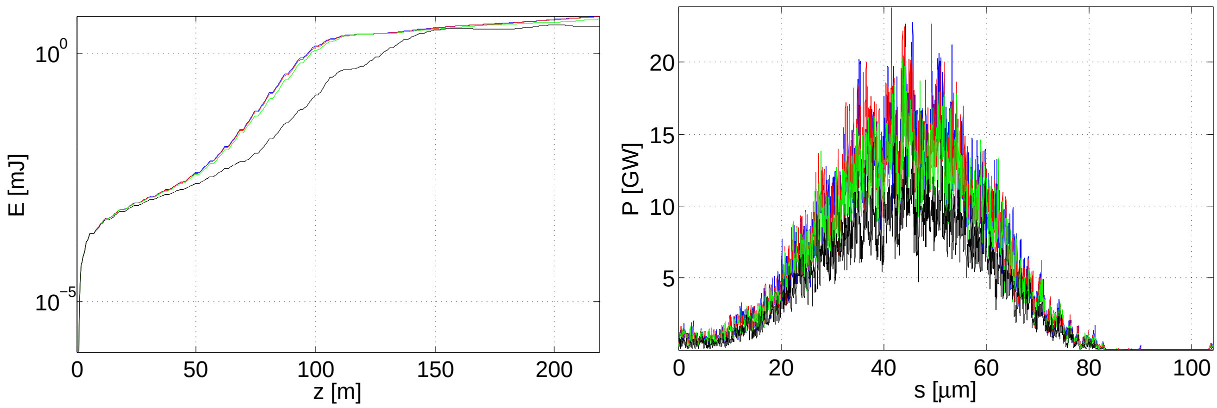

FIG. 11. Average radiation energies along the undulator length (left) and average radiation powers along the bunch length (right) at first (red-line), second (green-line), and third (black-line) iterations for one random seed. The results are compared with ones of without errors (blue-line).

The average radiation energy and power at each iteration of BBA procedure for one random seed are compared with the results of without errors in Figure 11. Before the BBA procedure, the distorted orbit produces the radiation energy and power much lower than 1 mJ and 1 GW, respectively. However the average radiation energy and power increase as iteration proceed. The peak value of average radiation energy is about 3.8, 4.9, and 5.6 mJ at first, second, and third iterations, respectively. The average radiation power also increases similarly during three iterations.

The SASE FEL radiation simulations are performed for more random seeds. Figure 12 shows the comparison of the peak values of average radiation energy and power with rms values of horizontal orbit trajectories after the BBA procedure for 10 random seeds. Within the 1–2 μm rms orbit

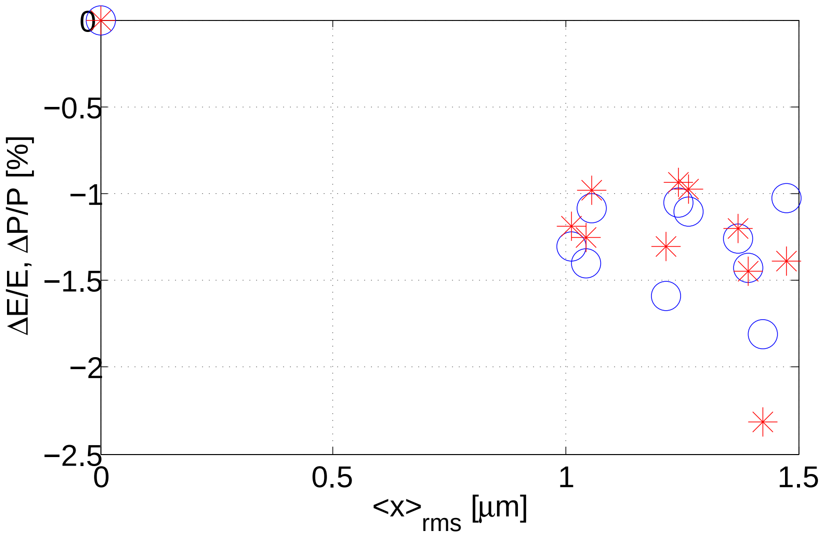

FIG. 12. Comparison of peak radiation energy (blue-circle) and peak radiation power (red-asterisk) with rms values of horizontal orbit trajectories after third iteration for 10 random seeds.

trajectories, the decrease of radiation energy and power is less than 3 %. The orbit trajectory acquired by the full procedure of BBA produces a reliable radiation in the SASE1 undulators.

VI. SUMMARY

The beam-based alignment using BPM readings of three beam energies was performed for the E-XFEL SASE1 undulators. The errors of quadrupoles and BPMs were taken into consideration in simulations, and these were calculated and corrected through the BBA procedure. The orbit trajectory less than 3 μm rms in regard to a straight line was achievable along the SASE1 undulators. In addition, the time-dependent SASE FEL radiation process was executed with the aligned orbit trajectories, where the orbit trajectory after BBA procedure generated a SASE FEL radiation with high reliability.

The BBA experiment was carried out for the FLASH undulators for two days in early 2013 with M. Vogt and D. Gu. The experiment produced the better transmission of the electron beam in the undulators, but the orbit trajectory was not successfully improved . The offline analysis has been continued with the output of the experiment and the next experiment will be made in the late 2013 or early 2014. The BBA study for the E-XFEL SASE1 undulators is expected to be useful to the FLASH BBA experiment.

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