ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO007

BEAM-BASED ALIGNMENT IN THE EUROPEAN XFEL SASE1

Hyunchang Jin, Winfried Decking, Torsten Limberg
DESY, Notkestrasse 85, 22603 Hamburg, Germany

Abstract

The European X-ray Free Electron Laser (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 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.

INTRODUCTION

The European X-ray Free Electron Laser (XFEL) [1] is a fourth-generation light source with high beam energy up to 20 GeV. There are three undulator systems in the XFEL to produce hard and soft X-ray pulses using the process of self-amplified spontaneous emission (SASE). In the 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. 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. 1. 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.

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. In this report, we apply this BBA method to the XFEL SASE1 undulators. Furthermore, the reliability of the orbit trajectory obtained by the BBA method is identified through the SASE FEL radiation simulation by using the three-dimensional, time-dependent FEL code, *GENESIS 1.3* [2]. The radiation energy and power induced by the aligned orbit trajectories are compared with those induced by a straight orbit trajectory.

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 [3]

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

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 $x + \beta$. For the XFEL SASE1 undulators, at least three beam energies are needed to identify the unknown parameters, the initial launch condition and misalignments of quadrupoles and BPMs. Therefore, beam energies, 8.0, 14.0, and 17.5 GeV, are selected within the XFEL operation modes in the following simulations.

BBA SIMULATIONS

The BBA simulation has been accomplished with a simulation code, *ELEGANT* [4]. 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 1.

Figure 2 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, and 1.4 mm for beam energies, 8.0,

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO007

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

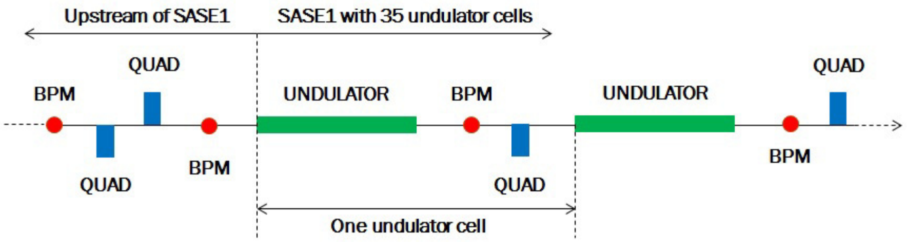

Figure 1: Schematic view of the XFEL SASE1 undulators. SASE2 has same structure with SASE1.

Table 1: List of errors used in simulations. Each error has a gaussian distribution.

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

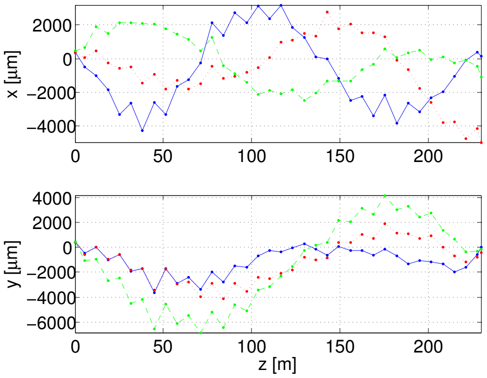

Figure 2: Horizontal (up) and vertical (down) orbit trajectories of three beam energies, 8.0 (blue), 14.0 (red), and 17.5 (green) GeV with quadrupole and BPM errors.

14.0, and 17.5 GeV, respectively, and the vertical rms orbit trajectories do about 1.5, 1.9, and 3.5 mm, respectively.

The misalignments of quadrupoles and BPMs and launch conditions are calculated and corrected with the BPM readings of three beam energies. Figure 3 shows the quadrupole positions, BPM readings, and orbit trajectories in the horizontal and vertical planes after a third 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 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 with respect to a straight line. In the vertical plane, those values are about 20, 7.9, and 1.8 μm, respectively. Consequently, these values are significantly improved through the three iterations. Especially, the rms orbit trajectories decrease noticeably from 1–3 mm to 1–3 μm in both planes. 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. For 100 random seeds, they show similar results about rms orbit trajectories. 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 1–3 μm for each beam energy.

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* [5] 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 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. 4. 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

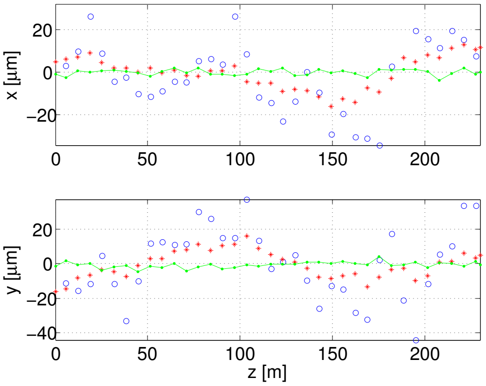

Figure 3: Orbit trajectories(green-line), quadrupole positions(blue-circle), and BPM readings(red-asterisk) in horizontal (up) and vertical (down) directions after third iteration at 17.5 GeV.

at the beam center in both planes and slice energy spread is also less than 0.2 MeV at the beam center.

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 Fig. 5. Without the errors, 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. 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 an iteration proceeds. The peak value of average radiation energy is about 3.8, 4.9, and 5.6 mJ after 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. Within the 1–3 μm rms orbit 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.

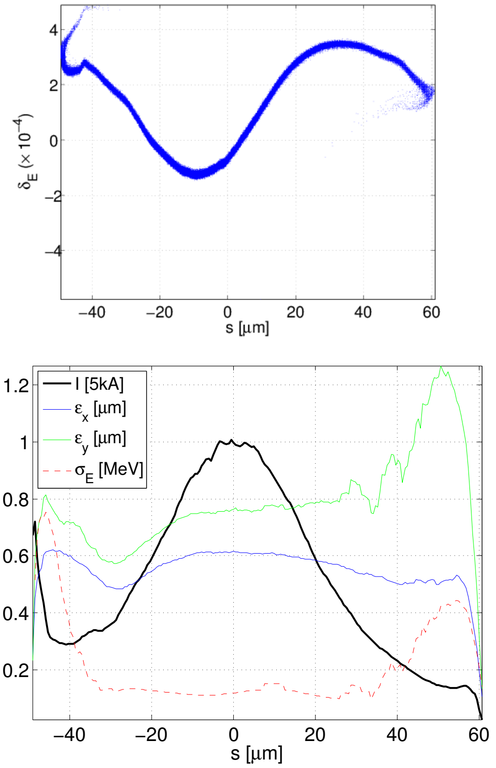

Figure 4: Longitudinal phase space (up) and beam profile (down) before SASE1 undulators. A beam current I (black-line), horizontal (blue-line) and vertical (green-line) slice emittances $\epsilon_{x,y}$, and slice energy spread σ_E (red-dashed-line) are shown in a beam profile. A bunch head is on the right side.

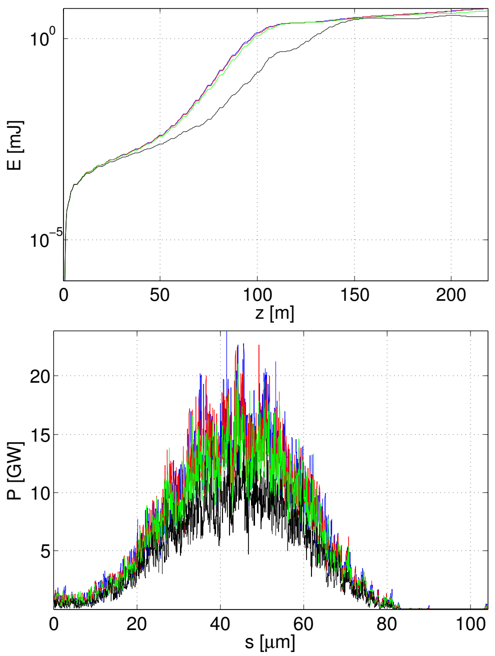

Figure 5: Average radiation energies along the undulator length (up) and average radiation powers along the bunch length (down) after first (red-line), second (green-line), and third (black-line) iterations. The results are compared with ones of without errors (blue-line).

SUMMARY

The beam-based alignment using BPM readings of three beam energies was performed for the 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. This BBA study for the XFEL SASE1 undulators is expected to be useful to the FLASH BBA experiment.

REFERENCES

[1] M. Altarelli et al., "The European X-ray free-electron laser", Technical Design Report, DESY 2006-097 (2006).

[2] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", Nucl. Instrum. Methods Phys. Res., Sect. A **429**, 243-248 (1999).

[3] P. Emma, "Beam Based Alignment of Sector-l of the SLC Linac (A/r).", Report No. SLAC-PUB-5787 (1992).

[4] M. Borland, "Elegant: A flexible SDDS-compliant code for accelerator simulation", Report No. LS-287 (2000).

[5] K. Flottmann, "Astra: A Space Charge Tracking Algorithm", `http://www.desy.de/~mpyflo/Astra_dokumentation/` (2013).

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.