ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP002

BEAM BASED ALIGNMENT IN ALL UNDULATOR BEAMLINES AT EUROPEAN XFEL

M. Scholz*, W. Decking, DESY, Hamburg, Germany
Y. Li, European XFEL, Hamburg, Germany

Abstract

The Free Electron Laser European XFEL aims at delivering X-rays from 0.25 keV up to 25 keV out of three SASE undulators. A good overlap of photon and electron beams is indispensable to obtain good lasing performance, especially for the higher photon energies. Thus the quadrupole magnets in the undulators must be aligned as good as possible on a straight line. This can only be realized with a beam based alignment procedure. In this paper we will report on the method that was performed at the European XFEL. We will also discuss our results.

INTRODUCTION

The European XFEL aims at delivering X-rays from 0.25 to up to 25 keV out of 3 SASE undulators [1,2]. The radiators are driven by a superconducting linear accelerator based on TESLA technology [3]. A schematic layout of the European XFEL is shown in Fig. 1. The linac operates in 10 Hz pulsed mode and can deliver up to 2700 bunches per pulse. The electron beam can be distributed to three different undulator beamlines within a pulse [4,5]. The European XFEL is being realized as a joint effort by 12 European countries. European XFEL's accelerator and major parts of the infrastructure are contributed by the accelerator construction consortium, coordinated by DESY.

The alignment of the magnets in FELs, especially in the undulator beamlines is crucial for top performance in the sense of maximum SASE pulse energy. This is especially the case with hard X-ray beamlines, which are extraordinarily sensitive to misalignments. In order to provide an efficient overlap between the electron and photon beams inside the undulator, the electron beam has to go through the undulators on a straight line with displacements below 10 μm. This alignment precision cannot be achieved by traditional optical alignment procedures thus beam based alignment (BBA) becomes necessary. The BBA procedure has been regularly carried out for all undulator beamlines at European XFEL. The method is well tested at other facilities [6, 7] and it was also studied theoretically for European XFEL [8] before the start of the commissioning. We will report on the BBA activities at European XFEL as well as on some results we have achieved so far.

UNDULATOR SECTIONS

The two hard X-ray undulator beamlines SASE1 and SASE2 (see Fig. 1) are build up with 35 undulator cells. SASE3, the soft X-ray undulator consists of 21 undulator cells [9]. Each cell is 6.1 meters long and is composed of the 5 m long undulator itself and a 1.1 m long intersection. The elements of the intersections are, inter alia, a beam position monitor (BPM) as well as a quadrupole magnet. The magnet is mounted on a mover that allow adjusting its position in both transverse directions. The undulator period length is 40 mm for the hard X-ray undulators and 68 mm for the soft X-ray undulator. Figure 2 shows a technical drawing of an undulator cell including the intersection. The beam position monitors in the intersections are cavity BPMs with a sub μm resolution [10]. This is crucial because the alignment has to be accomplished in the μm range.

BEAM BASED ALIGNMENT METHOD

The BBA method has been described in previously published papers and reports e.g. [6–8]. We will refrain from a further description in detail in order to leave room for the presentation of the BBA results. In summary: The goal is to find the offsets of all BPMs as well as of all quadrupole magnets. The concept is to measure the electrons' trajectory for different beam energies while the magnetic field of the quadrupoles is kept constant. This allows to distinguish between BPM offsets, which are not depending on the beam energy, and the quadrupole offsets which lead to an energy depending kick when the they are aligned off axis. The greater the energy difference between the measurement steps, the better the distinction between BPM and magnet offsets. The alignment procedure has to be carried out in several iterations until the final precision can be reached. BBA at European XFEL is carried out with four different electron beam energies, namely 10, 12, 14 and 17 GeV. 5-10 iteration are typically necessary to accomplish the BBA's goal. The whole procedure takes about 4-8 hours depending on the initial beamline setup. A significant part of the time is used to prepare all three undulator beamlines for beam transport with all four electron energies. The electron beam's energy is precisely determined for each energy step. This can be done most efficiently using the highly chromatic beam optics in the collimation section. Comparisons of measured and design trajectory responses to a horizontal kick upstream the collimations section allows to determine the beam energy to a precision in the per mille level. This ensures that the transfer matrices in the undulator, which are necessary to calculate the BPM and magnet offsets, are as precise as possible. For each energy, a machine setup is saved to a dedicated file, which can then be loaded during the BBA iterations within minutes. The fast kicker distribution system of European XFEL [4, 5] allows to do BBA for all three beamlines at the same time. The BBA iterations are always carried out from low to high beam energies.

* matthias.scholz@desy.de

39th Free Electron Laser Conf. FEL2019, Hamburg, Germany JACoW Publishing
ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP002

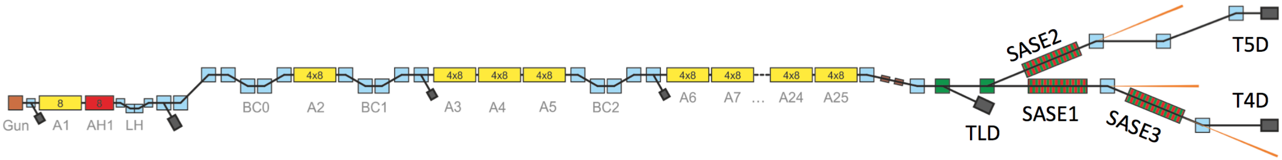

Figure 1: Schematic overview of the European XFEL. The injector including the electron gun, the first cryogenic 1,3 GHz acceleration module as well as the third harmonic RF-module are depicted on the left hand side. The next section contains the linac as well as the bunch compressors, followed by the collimation part and the beam distribution section. Finally the undulator beamlines are presented on right hand side.

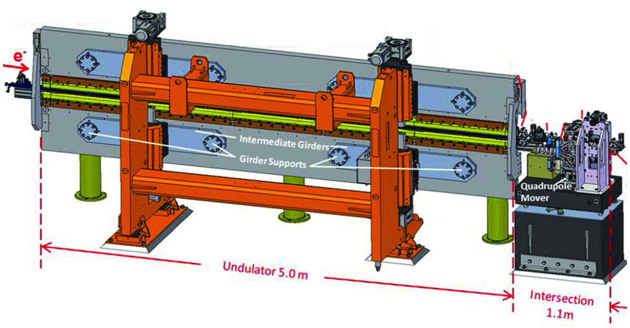

Figure 2: An undulator cell as used for European XFEL including the 5 m long variable gap undulator as well as a 1.1 m long intersection consisting, inter alia, of a beam position monitor and a quadrupole magnet.

RESULTS FROM BEAM BASED ALIGNMENT AT EUROPEAN XFEL

We will focus on some results from beam based alignment carried out at European XFEL that have been essential for FEL operation. These results are related to the hard X-ray beamlines SASE1 and SASE2, which are more sensitive to quadrupole magnet misalignments than SASE3. All undulator and photon beamlines were aligned initially with respect to a laser based straight line reference system. The expected alignment precision with respect to the straight line was in the range $\pm 100\ \mu$m. However, due to systematic problems with the reference system the alignment of the beamlines was not as good as expected. Figure 3 shows the BPM and quadrupole offsets of SASE2 in both planes determined with beam based alignment. Two curves in each plot represent the BPM and quadrupole data from a measurement in February 2018 while the other two graphs show the data from a BBA in August 2019. The first BBA carried out in 2018 showed clearly that the intersection elements of the beamline carying the BPMs and quadrupoles were misaligned. The offsets followed a sinusoidal curve with about one period over the undulator lengths and amplitude of about 1 mm. Realignment was arranged based on the data from the first BBA. Later measurements, e.g. the presented data from August 2019, showed that the new alignment was significantly better. Figure 4 and Fig. 5 show the offsets of 10 selected quadrupole magnets determined with BBA since the end of 2017. All offsets are plotted with respect to the current machine setup (August 2019). The first plot shows data from

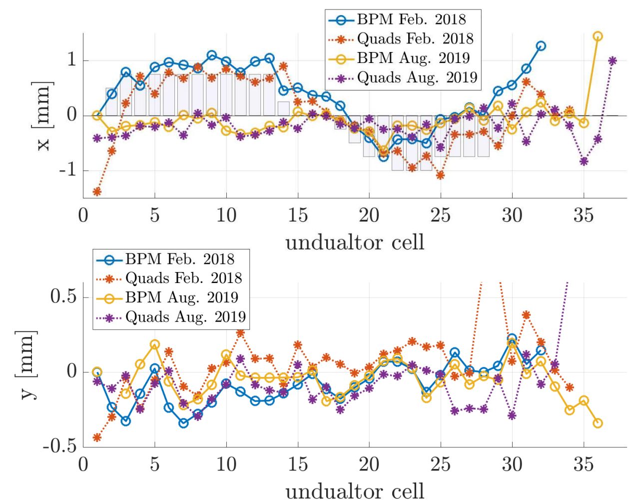

Figure 3: BBA result for quadrupole and BPM offsets from February 2018 and August 2019. The results from 2018 revealed a strong misalignment of the beamlines in the horizontal plane. This misalignment was correct. The correction offsets are depicted as bars in the upper plot. The BBA results form 2019 show that the realignment was successful.

SASE1 and the second plot depicts the same information for SASE2. Our BBA learning curve can be reconstructed from these plots. It is clearly visible that the relative offsets were constantly large or did even oscillate with large amplitudes around the current value. However, we converged to solutions that are close to what we use right now. This could be achieved with the BBA carried out in January 2019 for SASE1 and with the BBA carried out in April 2019 for SASE2. The major changes were: The electron beam energies were determinded more precisely for each energy step. And all iterations started with the lowest and ended with the highes beam energy. Before that the beam energy was changed in one iteration from lowes to highest energy and in the next iteration in the opposite direction. Furthermore, more time was spend to keep the launch trajectory to the undualtor the same for all measurements within one interation. The SASE pulse energy could be increased with these BBAs in the respective beamlines. The pulse energy development over the last year for SASE1 and SASE2 can be found in Fig. 6. The maximum SASE level in SASE1 was in the range of 1.5 mJ in 2018. The BBA carried out in January 2019

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP002

helped to achieve up to 3 mJ at 9.3 keV photon energy and 4 mJ at 7 keV in the following moths. Operation of SASE2 was difficult until April 2019. The SASE pulse energy was typically in a range of 300-400 μJ. The BBA carried out on April 3, 2019 changed the situation completely. SASE2 pulse energies are since that alignment typically close to the pulse energies of SASE1.

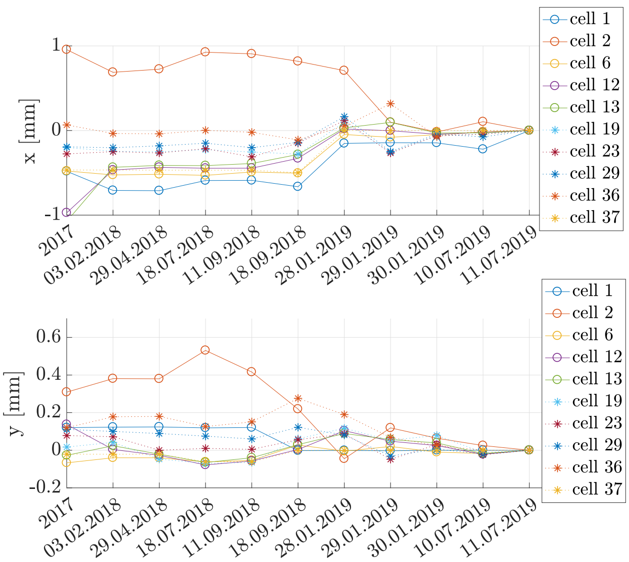

Figure 4: Relative quadrupole offsets of 10 selected magnets in the SASE1 beamline. All offsets are plotted with respect to the current machine settings (August 2019). The offsets' variation from one BBA to the next became smaller with the measurement carried out at the beginning of 2019.

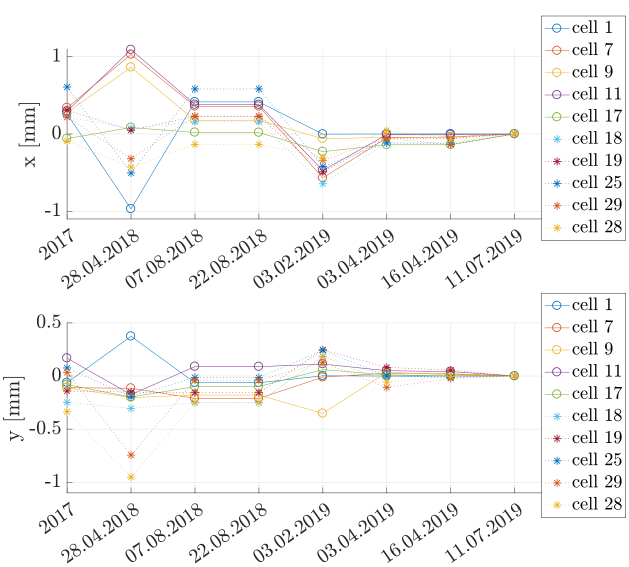

Figure 5: Relative quadrupole offsets of 10 selected magnets in the SASE2 beamline. All offsets are plotted with respect to the current machine settings (August 2019). The offsets' variation from one BBA to the next became smaller with the measurement carried out in April 3, 2019.

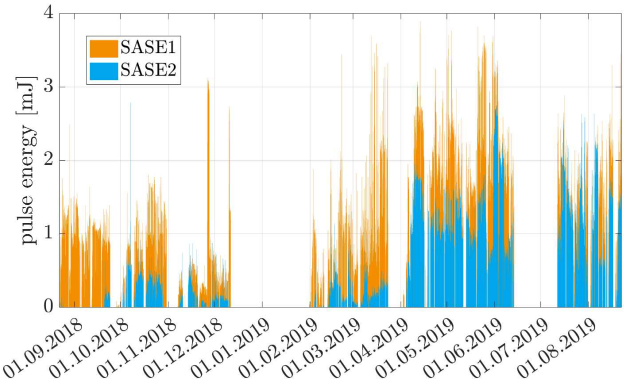

Figure 6: SASE pulse energy development for the hard x-ray undulator beamlines SASE1 and SASE2 during the last year. The BBA carried out at the beginning of February 2019 helped to increase the pulse energy of SASE1 significantly. The improvment due to the BBA in SASE2 carried out at the beginning of April 2019 is even more significant.

CONCLUSIONS AND OUTLOOK

We improved the BBA procedure during the last months and could achieve a significant increase of the SASE pulse intensities in both hard X-ray beamlines of European XFEL, SASE1 and SASE2. A strong misalignment of the SASE2 beamline could be found due to the BBA procedure. The realignment was carried out successfully based on the BBA data, which was confirmed by the results of the next BBA. We will continue to work on the procedure in order to improve the result even further. The goal is to align all undulator beamlines with offsets below 10 μm which could not yet been achieved.

ACKNOWLEDGMENT

We like to thank all colleagues who have been involved the operation of the European XFEL.

REFERENCES

[1] M. Altarelli *et al.*, "The European X-Ray Free-Electron Laser, Technical design report", DESY-06-097, July 2007. doi: 10.3204/DESY_06-097

[2] R. Brinkmann *et al.*, "TESLA XFEL: First stage of the X-ray laser laboratory. Technical design report, supplement", DESY 02-167, March 2002.

[3] R. Brinkmann *et al.*, "TESLA Technical Design Report – Part II: The Accelerator", DESY 01-011, March 2001.

[4] S. Liu *et al.*, "Parallel Operation of SASE1 and SASE3 at European XFEL", presented at FEL'19, Hamburg, Germany, 2019, paper TUA01, this conference.

[5] L. Fröhlich *et al.*, "Multi-Beamline Operation at the European XFEL", presented at FEL'19, Hamburg, Germany, 2019, paper WEP008, this conference.

[6] P. Emma, R. Carr, H.-D. Nuhn, "Beam-based alignment for the LCLS FEL undulator", *Nuclear Instruments and Methods*

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THP002

in Physics Research A, vol. 429, pp. 407-413, 1999. doi:10.1016/S0168-9002(99)00117-5

[7] Y. Woon *et al.*, "Automation of beam based alignment for the PAL-XFEL undulator line", *Nuclear Instruments and Methods in Physics Research A*, vol. 782, pp. 120-125, May 2015. doi:10.1016/j.nima.2015.02.009

[8] H. Jin, W. Decking, T Limberg, "Beam-based alignment in the European XFEL SASE1", TESLA-FEL 2013-03, 2013.

[9] S. Abeghyan *et al.*, "First operation of the SASE1 undulator system of the European X-ray Free-Electron Laser", *J. Synchrotron Rad.*, vol. 26, pp. 302–310, 2019. doi:10.1107/S1600577518017125

[10] D. Lipka, "Very First Experience with the Standard Diagnostics at the European XFEL", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 180–183. doi:10.18429/JACoW-IPAC2017-MOPAB043