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AUTOMATION OF THE UNDULATOR MIDDLE PLANE ALIGNMENT RELATIVE TO THE ELECTRON BEAM POSITION USING THE K-MONOCHROMATOR

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Abstract

The correct K value of an undulator is an important parameter to achieve lasing conditions at free electron lasers. The accuracy of the installation of the undulator in the tunnel is limited by the accuracy of the instruments used in surveying. Moreover, the position of the electron beam also varies depending on its alignment. Another source of misalignment is ground movement and the resulting change in the position of the tunnel. All this can lead to misalignment of the electron beam position relative to the center of the undulator gap up to several hundred microns. That, in turn, will lead to a deviation of the ΔK/K parameter several times higher than the tolerance requirement. An automated method of aligning the middle plane of the undulator, using a K-monochromator, was developed and used at European XFEL. Details of the method are described in this article. The results of the K value measurements are discussed.

INTRODUCTION

The European X-ray Free Electron Laser (EuXFEL) produces spatially coherent photon pulses in the energy range from 0.26 to 29.2 keV at electron beam energies of 10.5 GeV, 14 GeV, or 17.5 GeV [1].

It has two hard X-ray Self-Amplified Spontaneous Emission (SASE) undulator systems and one soft X-ray SASE undulator system for producing high brightness laser radiation.

The hard X-ray undulators SASE1 and SASE2 consist of 35 undulator segments, each 5m long with a 40 mm magnet period, separated by 1.1 m long intersections for e-beam steering, focussing, and phase adaptation. In case of the soft X-ray undulator (SASE3) the setup is similar but has 21 segments and a longer magnet period of 68 mm [2].

In order to get a correct K value of an undulator, the middle plane of the undulator gap must coincide with the trajectory of the electron beam. Therefore, it is important to have the ability to adjust the middle plane of the undulator gap relative to the electron beam.

REQUIREMENTS FOR UNDULATOR SYSTEMS

One prerequisite for achieving lasing is the tuning of the K-value of all undulator segments to a very high precision. The undulator segments are characterized by the K-parameter: $K = \frac{eB\lambda_u}{2\pi m_e c}$, where B is the effective magnetic field and λ_u is the undulator period.

From FEL tolerance calculations, it can be shown that the relative error in the produced wavelength must be smaller than the Pierce parameter ρ. ρ is a fundamental scaling parameter and gives a measure of the exponential gain and saturated efficiency of a high-gain FEL, with typical values in the X-ray regime of $10^{-4} \leq \rho \leq 10^{-3}$ [3, 4]. The error in K for the given error in λ at 1 Å (~12 keV photon energy) is approximately $3 \cdot 10^{-4}$ and determines the required K-measurement accuracy.

This magnetic tuning and calibration of the undulators was done in the lab before the transport to the final position in the tunnels. Mounted in the tunnels there is no possibility to measure the K-values precisely enough by means of magnetic measurements. Photon-based commissioning [5] of the European XFEL undulators requires a precise adjustment of the K-parameters of all undulator segments and phasing between these segments. The undulator commissioning spectrometer, also known as K-Monochromator or K-Mono, which is in essence a hard x-ray monochromator based on a Si(111) channel-cut crystal, makes it possible to measure the spontaneous radiation of the undulator segments for K-tuning and other diagnostic measurements (e.g. pointing, phase matching) [3, 6, 7].

One important goal is the characterization of the undulator segments with a well-defined electron orbit after electron-beam based alignment and once lasing was established. In this case a database of energy spectrum measurements for each undulator segment will make it possible to identify changes due to radiation damage or changes in the mechanical alignment

K VALUE MEASUREMENT METHOD

There are several methods for K-tuning, phase matching, and trajectory alignment for which the K-mono can be used [3, 6, 7]. Here we have used the K-mono with SR-imager, a highly sensitive imager with a big field of view (27 mm x 15 mm), for observing the spatial profile of the spontaneous radiation of single undulator segments [5]. During our tests this appeared to be the fastest method.

When tuning the K-mono to photon energies slightly below the resonant energy of the undulator segments, donut-like rings appear, as the divergence angle of the spontaneous radiation depends on the photon energy and the off-axis spectrum gets ‘red-shifted’. For even harmonics the on-axis flux is zero, but flux can be observed at an angle of only a few μrad away from the axis.

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The diameters of the rings depend on gap settings, e-beam energy, detuning factor, and distance to the undulator segment. With these parameters known with high accuracy, the K parameter can be determined directly from the ring diameter, which is a measure for the observation angle Θ in the undulator equation:

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \theta^2\gamma^2\right). \quad (1)$$

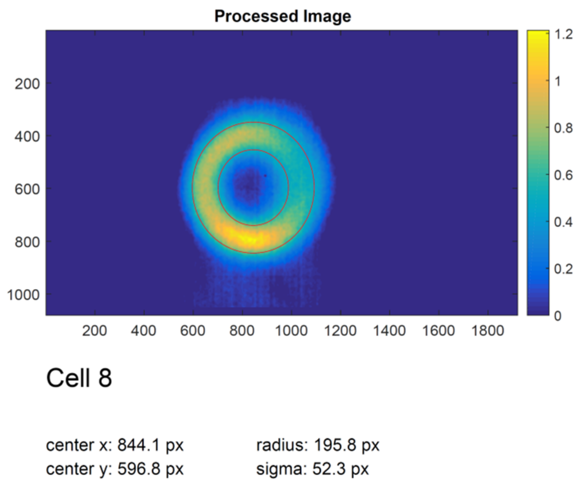

Figure 1: Example of online ring fitting, here for undulator segment 8 of SASE1.

For relative K tuning of the segments it is sufficient to tune to the same spatial profile by taking into account the geometrical factor of different distance to the screen, since all other parameters are equal for the segments. When looking more precisely, there is a slight distortion in vertical direction, and therefore a slightly larger vertical ring diameter due to the 2-bounce mode of the monochromator with the dispersion in vertical direction. Due to the large distance to the source point the acceptance angle of the monochromator crystal is small (10 to 20 µrad) and this effect can be neglected. For very precise measurements the beam should always be vertically centred on the screen, in order to avoid small energy shift. From the rings also the spatially integrated intensity and the beam pointing can be determined.

For the SASE1 undulator we have performed three complete scans where segment by segment was closed to the nominal K-value for 9.3 keV photon energy while all other segments were opened. The fitting algorithm was applied to the images to determine the ring diameters and subsequently the K-values (see Fig. 1). Two independent measurements (repeated after two hours) were performed in July in order to estimate the measurement error, including drifts of e-beam energy and position as well as electronic noise. This scan was repeated in October after the vertical alignment of cell 8 (green curve in Fig. 2).

The slight slope on the measurements from July is caused by a residual linear taper setting along the undulator system. Besides that the correlation of the curves is quite good, considering that three months passed between the measurements and beam parameters changed.

Most notably the deviation at cell 8 has vanished after the vertical alignment (described below). The measurement of cell 3, which is the first cell of the undulator, is not reliable, since there was no clear ring image. These measurements show that the RMS value of ΔK/K for the entire SASE1 system, without middle plane adjustment and excluding applied linear taper, is ~ $4.3 \cdot 10^{-4}$.

UNDULATOR MIDDLE PLANE CONTROL

The gap of the undulator is controlled by four servo motors. Two motors are controlling the upper strong back and the other two motors are controlling the lower strong back. The control system of the undulator is done by means of Beckhoff TwinCAT. The feedback value of the gap could be obtained either from the rotary encoders installed on the motors, or from two linear encoders, located on both sides of the undulator and directly measuring the gap between the magnet structures (see Fig. 3). For the standard operation the linear encoders are used for the undulator gap feedback. It is done in the following way. The linear encoders are measuring the distance between the magnet structures. The PLC is reading this value with 1 kHz frequency. The difference between the gap value provided by the rotary encoders and the linear encoders is measured during a PLC cycle. This information is used for feedforward correction to the rotary encoders in the sequencing PLC cycle. Thus, it is possible to achieve the truth-measured gap value with a delay of one millisecond.

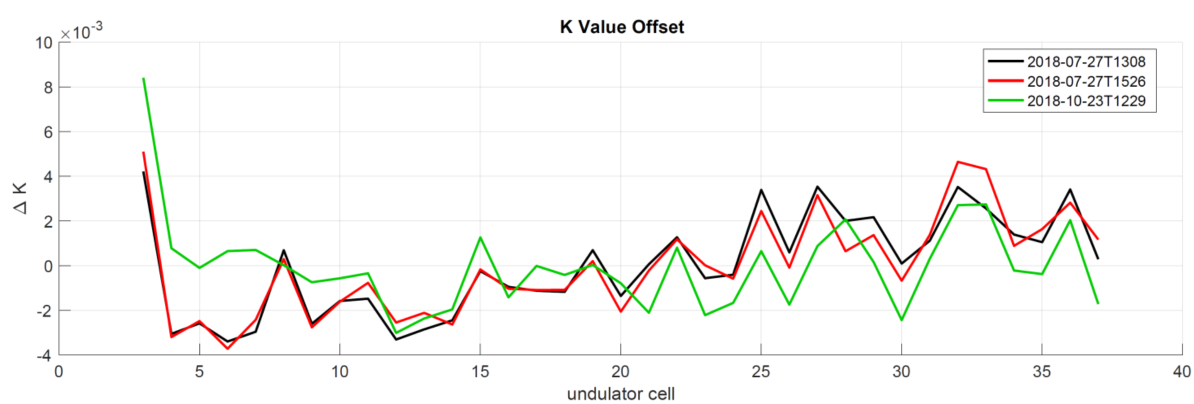

Figure 2: K value measurement results for SASE1 undulator system.

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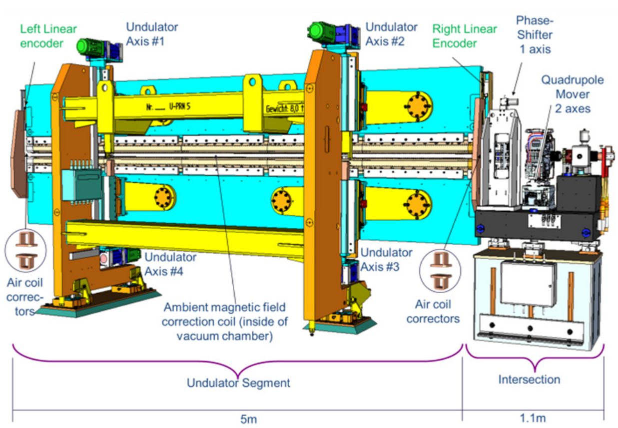

Figure 3: Undulator cell, consisting of undulator segment and intersection.

Similarly, the vertical offset of the middle plane of the undulator gap is realized. Depending from the direction, the vertical offset is added or subtracted as an additional correction value to the rotary encoder values.

The Distributed Object-Oriented Control System Framework (DOOCS) is used for the control of the accelerator at European XFEL. Therefore, the interface to DOOCS is provided for the vertical offset scan. Figure 4 shows a DOOCS client panel for control of the undulator middle plane.

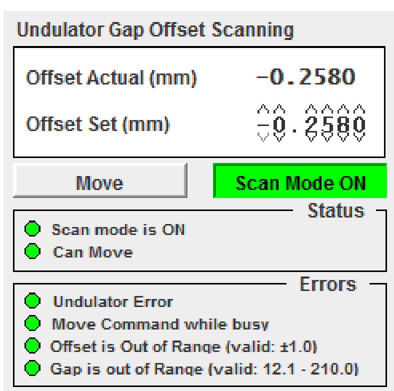

Figure 4: GUI for the manual control of the undulator middle plane.

Every undulator cell is equipped with DOOCS location for the middle plane scan control. The operation consists of the following life-cycle:

- Cell preparation. This is done from the local control console only. The step ensures Undulator control system safety, allowing only authorized operations. This action is internally referred as Enable Scan Mode.
- Switching Scan Mode ON. This can be done locally as well as remotely from DOOCS.
- Set target offset in milimeter unit and issue start command.

Figure 5 shows the undulator middle plane scan program flowchart.

The interface to the DOOCS control system allows to automatize the process of the undulator middle plane scan measurement by means of the Matlab script. This script drives the undulator to desired K value, implementing the gap offset, taking the images, and fitting the ring diameters. After the finishing the offset scan for current undulator, the gap is driven to the value, where the magnetic field of the undulator is negligible, which is 100mm. Afterward the measurements are made on the subsequent undulator. For one scan from -0.5 mm to +0.5 mm in 0.1 mm increments, approximately four minutes are required.

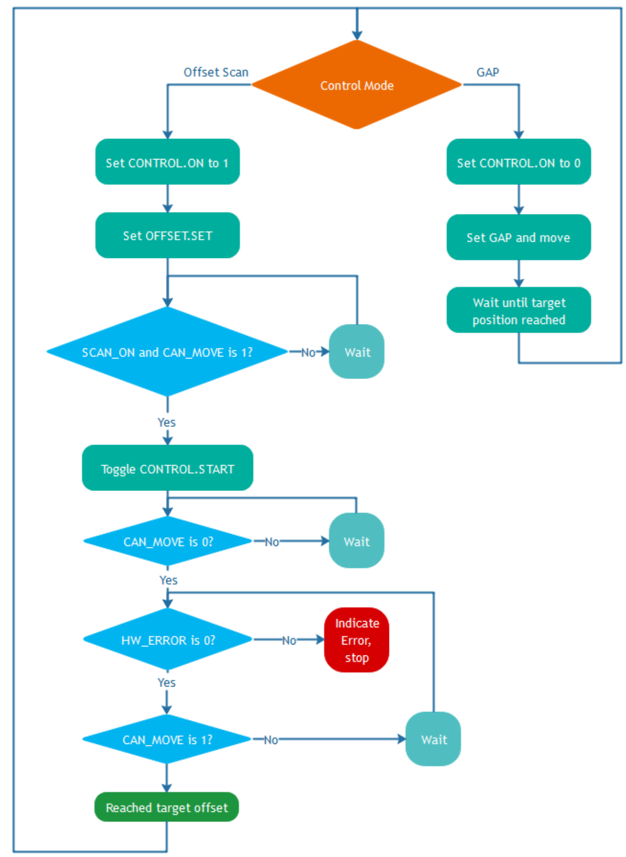

Figure 5: The flow chart of the undulator middle plane scan program.

DATA ACQUISITION AND ANALYSIS

From tuning of lasing in the SASE1 undulator system, it was suspected that the middle plane of undulator segment 8 was not centred with respect to the electron beam. This suspicion was verified with a procedure for finding the vertical magnetic centre of the undulator gap

The variation of peak field and K-parameter along y is calculated using Eq. (2), and shown in Table 1, using SASE1 undulator period [8]:

$$\frac{\Delta K}{K} = \frac{1}{2}\left(\frac{2\pi y}{\lambda_u}\right)^2, \; y = \frac{\lambda_u}{2\pi}\sqrt{2 \cdot \frac{\Delta K}{K}}. \qquad (2)$$

The vertical deviation from the presumed magnetic axis of the undulator (y-offset) was varied in steps of 100 µm while keeping the gap constant. In the actual vertical centre of the undulator gap the magnetic field (and with it the K value) is minimal, thus the resonance photon energy

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is maximized. The K-mono is tuned below the undulator resonance, therefore the difference between resonance energy and K-mono energy is higher and thus the ring diameter is larger. From Table 1 we can derive that a vertical offset of 200 µm from the centre corresponds to a deviation of K in the order of the Pierce parameter.

Table 1: ΔK/K Variation Along Y

y [mm] offset from center	ΔK/K resulting deviation from nominal K
0	0.0
0.1	0.000123
0.2	0.000493
0.3	0.001110
0.4	0.001973
0.5	0.003084

With the measured data and the best-fit curves (see Fig. 6) we could determine the best vertical undulator position to -306 µm offset with an estimated positioning error of less than 100 µm from the centre, which is better than the requirement. It is difficult to determine an error bar for each measurement point. The two points at the zero position were measured before and during the scan. The possible reason for the deviation could be the electron beam condition, since the beam energy as well as orbit jitter (e.g. from feedback control) were not taken into account in this measurements. The undulator middle plane control accuracy could also be a reason for this. For each measurement point we have taken more than one hundred pictures.

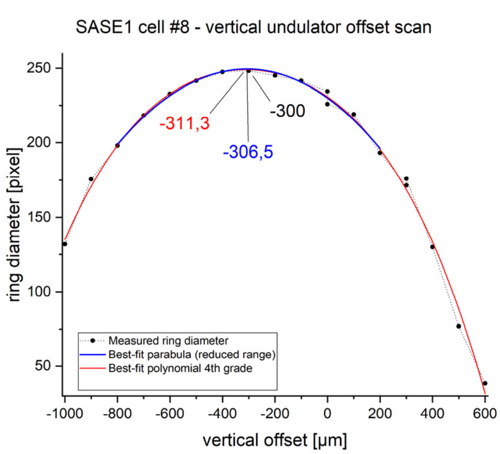

Figure 6: Ring radius versus vertical undulator offset.

When using a 2D Gaussian fitting algorithm on different samples of this data set we get only small errors (for sufficiently large rings greater than 100 pixels) which could not explain the deviation.

CONCLUSIONS

The correct value of the K parameter is one of the most important conditions for the operation of a free electron laser. There are many sources of errors of the resonant radiation of the undulator. These include deviations of the energy, position and angle of the electron beam (1), as well as the accuracy of the gap positioning or the local temperature of the undulator magnetic structures. Nevertheless, the results of measuring the K value, for example, in SASE1 showed that even without additional adjustment of the vertical position of the undulators middle plane, the RMS value of ΔK/K is very close to the Pierce parameter.

First automated procedures were used to measure the K value for all 35 segments of the SASE1 and SASE2 undulators and acquire a full data set in a reasonably short time of less than 45 minutes.

An automated procedure to scan the position of the undulator middle plane relative to the electron beam position was implemented. The scan time of one undulator segment during our measurements is four minutes, but it can be significantly reduced by optimizing the communication process between the local PLC and the DOOCS control. There is still a large potential for improvements by optimization of the procedures in terms of speed, accuracy, and functionality. It is planned to use the system for regular undulator inspections, e.g. for assessing radiation damages to the undulators, for which we need mainly improvements on the software side. Procedures will be further developed for automated K- and hard x-ray FEL spectrum measurements

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