GENERAL STRATEGY FOR THE COMMISSIONING OF THE ARAMIS UNDULATORS WITH A 3 GeV ELECTRON BEAM

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Abstract

The commissioning of the first SwissFEL undulator line (Aramis) is planned for the beginning of 2017. Each undulator is equipped with a 5-axis camshaft system to remotely adjust its position in the micrometer range and a gap drive system to set K-values between 0.1 and 1.8. In the following paper the beam-based alignment of the undulator with respect to the golden orbit, the definition of look-up tables for the local correction strategy (minimization of undulator field errors), the fine-tuning of the K-values as well as the setting of the phase shifters are addressed. When applicable both electron beam and light based methods are presented and compared.

INTRODUCTION

The large number of undulator modules required in a free electron laser (FEL) makes the commissioning of a beamline more involved than in a synchrotron where the light source consists (regularly) of a single device. Thirteen U15 modules (assuming to use also the spare unit), each 4 m long, will be operated together in the first SwissFEL hard X-ray line (called Aramis). It requires a precise control of the K-value of each unit within 100 ppm, a steering of the electron beam trajectory better than 2 μm RMS and a phase error of less than 5° RMS over a 4 m long unit.

All the SwissFEL undulators will be tested and optimized in the PSI magnetic measurement laboratory before the installation in the accelerator tunnel, see [1]. Nevertheless residual field errors together with the tight tolerances indicate the need of commissioning individual undulator modules directly with the beam as already experienced in comparable facilities [2]. Additional correction magnets are installed between undulator units and procedures are defined to improve the performance of the FEL during the commissioning and operation time.

In the following the different measurements together with the correction strategy are presented in the preliminary sequence planned for the commissioning of the beamline at the starting electron energy of 3.0 GeV.

UNDULATOR E-BEAM BASED ALIGNMENT

When the electron beam energy of at least 3 GeV (5.8 GeV is the nominal energy) is attained in the linac and transported to the undulators, the commissioning of the line can technically start. During the beam-based alignment (BBA) the undulators are set at open gap where the low magnetic field should minimize the orbit errors. An alternative candidate for the BBA is the nominal gap where the undulator is magnetically optimized.

Definition of the Reference Orbit

The first step is the definition of a reference orbit using BBA technique. For the SwissFEL a novel approach has been developed, as described in details in [3]. The proposed algorithm is based on the minimization of the deviation of the correction required to steer the beam to BPMs (beam position monitors) centers.

The BBA method in operation at the LCLS [4] is considered a valuable back up in case the baseline solution will not give satisfactory results. It is established on the BPMs reading at different beam energies (dispersion measurements) but the algorithm is rather complex and the full procedure is time consuming [5].

Once this phase is completed the undulators have to be aligned to the reference orbit as described in the following.

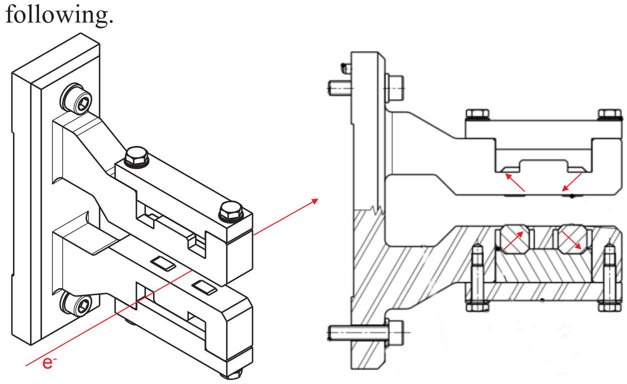

Figure 1: Alignment quadrupoles, on the left the 3D drawing with the detail of the beam axis, on the right the front view with the details of the magnets and magnetization directions.

Alignment Quadrupoles Technique

The axis of a planar undulator (light linear horizontal polarized) is the region where the vertical field (By) is minimum and where the longitudinal field (Bs) is zero. This definition identifies clearly the axis on the vertical plane while leaves some margin in the horizontal where a mechanical reference is used.

Taking the axis as a reference has the advantage to reduce the requirements on the alignment accuracy (dBy/dy=0) and to minimize the kicks due to the natural focusing on the vertical plane. Choosing a reference injection orbit with specific magnetic properties simplifies the challenging task of matching the field of different undulator modules which shall work together as a single device to make the FEL lasing.

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On the Hall sensor bench in the PSI magnetic measurement laboratory [1] the undulator axis is measured and transferred to an external reference. Two small permanent quadrupole magnets (called Qal, see Fig. 1) are used for this purpose, one upstream and one downstream the undulator, to outline the undulator axis through their magnetic centers.

Once installed in the beamline, the undulators can be then beam based aligned as follow. Starting from the reference orbit with all Qal off, the upstream alignment quadrupole of a generic unit is activated and the undulator is moved both horizontally and vertically. Monitoring the downstream BPMs, the center is defined where the reference orbit reading is recovered. After removing the upstream quadrupole, the same procedure is applied to the downstream quadrupole. Once these two points of the axis are measured, it is possible to calculate the height and the horizontal position together with the correct pitch and yaw angles and to align the undulator with a 5-axis camshaft mover system.

The alignment quadrupoles are used only during the alignment phase and they are taken off during the operation of the FEL. They are made of permanent magnets and they are removed by mean of a pneumatic system remotely controlled from the control room.

IN SITU CORRECTION OF MAGNETIC FIELD ERRORS

Once the alignment is completed the residual field errors shall be measured. A set of corrector magnets with a strength up to 200 G×cm can be used to compensate both the first and second field integrals.

Originally this was planned only for the horizontal plane where systematic kicks are expected. A hybrid magnetic structure, made of permanent magnet and iron poles, can be optimized only for a given gap and it shows residual field errors at different apertures. Nevertheless the experience with the U15 prototype indicates that field errors of the same strength are also present in the vertical plane.

Finally, four magnets, two dipoles upstream and two downstream, have been organized for the correction of the residual field errors in both planes.

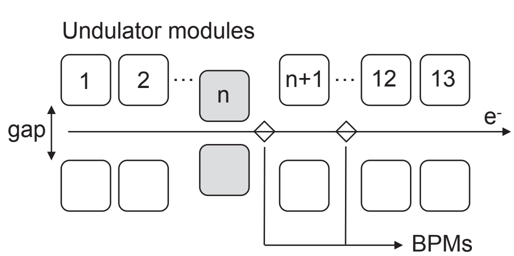

Figure 2: Measurements of the residual field errors with the help of the two downstream BPMs.

Starting with all modules opened, the BPM readings are recorded while the undulators are closed one by one, see Fig. 2. To simplify the data analysis, the quadrupole downstream the tested module shall be switched off. In case this creates problem for the transport to the beam dump, it is enough to switch off the first quadrupole (better the first two) after the undulator. This guarantees at least two "clean" BPMs for the analysis of the field error. Once the position at the BPMs is recorded, it is fairly simple to estimate the residual field integrals as a function of the gap. With an electron beam energy of 3.0 GeV, a BPM resolution of 1.0 µm and a distance between BPMs of about 4.7 m, it is possible to estimate the first field integral with a resolution better than 5 G×cm, enough to produce accurate look-up tables for the operation. But in case higher resolution is required, the electron energy can be further reduced.

After implementing the new look-up table, it is important to check the impact on the alignment, repeating the procedure described in the previous section before proceeding with further tests.

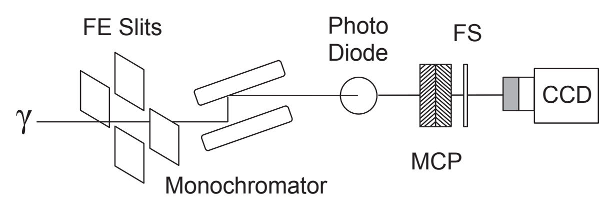

Figure 3: Schematic view of the photon diagnostic required for the commissioning of the U15 modules.

PHOTON BASED FINE-TUNING

For the commissioning of the undulator line a photon diagnostic section is required. As schematically represented in Fig. 3 the minimum requirements consist of a pair of front end slits to shape the beam, a double crystal monochromator with a selectivity better than 10^{-4}, a photodiode to measure the intensity and a MCP (micro-channel plates) followed by a fluorescent screen to image the beam profile on a CCD camera. The first measurement planned concerns the adjustment of the K-value as described in the following.

K-value in-Situ Calibration

The requirement (given by the FEL bandwidth) of a K-value uniformity among the modules of 10^{-4} is very challenging and cannot by easily achieved relying only on the magnetic measurements. The reproducibility of the Hall sensor bench is well within this range but the absolute accuracy is not better than 0.25%. In case the probe has to be changed or simply recalibrated during the test campaign, this would not guarantee enough homogeneity among the magnetic model of individual modules.

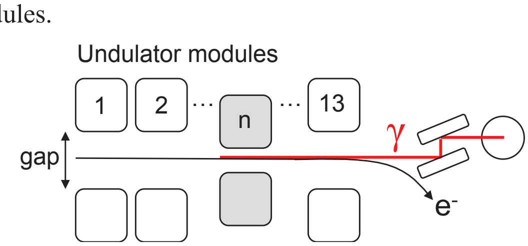

Figure 4: The calibration of the K-value is schematically represented for the nth undulator module (grey).

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The in-situ measurement of the K-value shall be done at the beginning around the nominal value of 1.2 for all the modules. The monochromator is set to the photon energy of 3.3 keV and the K-value is changed between 1.18 and 1.22 in steps of 10^{-4} while the intensity of the monochromatic radiation is measured on a photodiode and recorded (see Fig. 4). To accurately compare the results from different undulators, the impact of the different undulator locations (estimated in 0.1%) shall be taken into account. To overcome this difficulty it is possible to measure directly the total flux, i.e. the flux integrated over the full solid angle. It requires a sufficiently large aperture before the monochromator, in general about $3/\gamma\times L$, where L is the longest distance from the source, see Fig. 5 (calculations performed with the computer code SPECTRA [6]). A more detailed discussion about the advantages of measuring the total flux can be found in [2].

This procedure shall be repeated for the full operational range of K between 1.0 and 1.8 in steps of 0.1. With these data, look-up tables can be produced that allow a reliable operation of the undulator. Before completing this task, it is better to verify the undulator alignment (height and pitch).

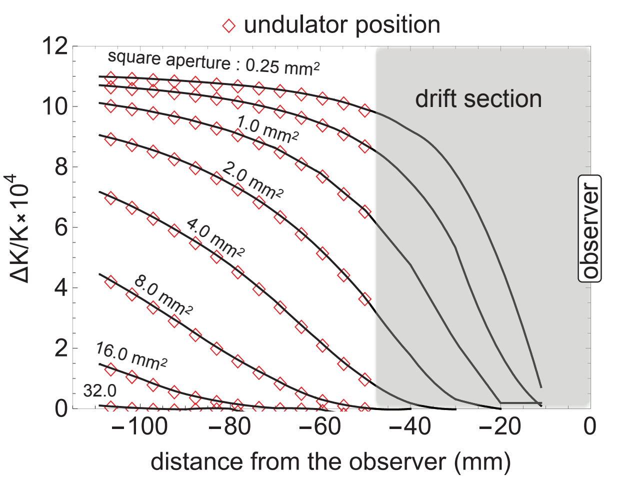

Figure 5: The position of the blue edge of the spectra in units of K-value for different square apertures.

Height and Pitch Adjustment

If an undulator module is misaligned and operated out of the axis, it is visible in the spontaneous radiation. When the electron bunch crosses the undulator parallel but above (or below) the axis, the energy of the photon is reduced. A simple way to measure the vertical offset, is to fix the monochromator energy at the nominal value and scan remotely the height. The maximum flux is at the position of the correct height.

The pitch of the undulator can also be optimized looking at the slope of the flux in the blue edge side. Electrons, which cross the undulator axis with a pitch angle, experience different K-values thus increasing the spectral width. Maximizing the slope is an effective way to get rid of the undesired pitch.

In the soft X-ray line, Athos, where Apple III undulators will be implemented [7], the same procedure can be used to align them also in the horizontal plane and in the yaw angle.

Correction of the Pointing Direction

After applying all the corrections previously described, the electron beam trajectory over the undulator line should be straight. Nevertheless it is considered safer to have the possibility to cross check it also versus the pointing direction of the spontaneous light. For this measurement all the undulator modules have to be prepared in lasing operating conditions but it is better without a lasing signal. This configuration is easily achieved: it is enough to close all modules at the same gap and leaving the phase shifter in random configuration to minimize the synchronization between modules. This last operation is not strictly required but it helps to improve the measurement quality, reducing the background.

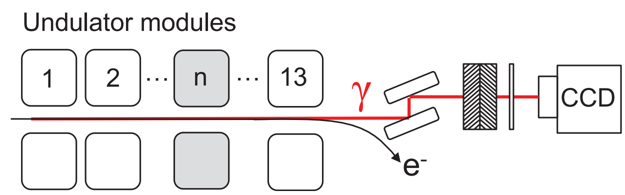

Figure 6: Schematic view of the measurement of the pointing direction of the nth undulator module (grey).

Then, one by one, each undulator module has to be detuned from the others changing its K-value of few percent while locking the monochromator at this new energy, see Fig. 6. The photon beam at the exit of the monochromator carries only information about the selected module. Imaging the mono-beam with the help of a MCP and a CCD camera gives its pointing direction. Repeating this procedure for each module and using the upstream dipole corrector to change the injection angle, the different spots from the different modules can be forced to overlap and new look-up table can be produced.

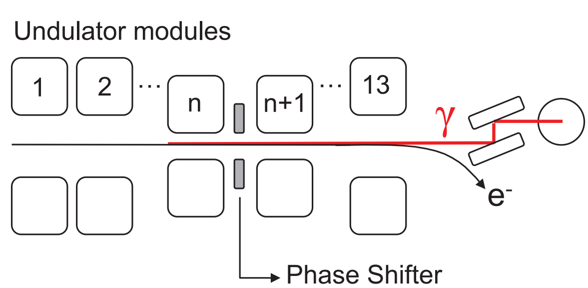

Figure 7: Schematic view of the setting-up of the n-th phase shifter. In the picture there is represented only the phase shifter under test.

Setting Up of the Phase Shifters

To achieve lasing the spontaneous radiation of different modules have to be in phase. Between modules a compact (few centimeter long) variable strength magnetic chicane (phase shifter) is installed to precisely delay the electron

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in order to tune the phase of the radiation in the downstream module. They are designed to rotate the phase of more than 4π for any K-value. There are both available simulations and magnetic measurements to calibrate the field of the phase shifter but it requires also a precise knowledge of the longitudinal position of each modules. At nominal K-value (1.2) an error of 1 mm introduces a phase of about 14°. More precise survey measurement and alignment of the modules can simplify the setting of the phase shifter but an in-situ calibration helps to optimize the intensity in case the nominal performances are not achieved. The radiation out of two neighboring modules, previously tuned to operate at the same K-value, has to be measured while the phase (the strength of the phase shifter) is changing, see Fig. 7. The recorded intensity signal changes periodically and the phase correlating to the maximum intensity has to be retained. This procedure has to be repeated for all K-values.

Measuring the Wakefield

The electron bunch looses energy while traveling across the undulator chain. There are two main mechanisms involved; the first concerns the energy radiated by the FEL process, the second one concerns the energy radiated because of the wakes. This last effect is expected to be the largest in the SwissFEL because of the small undulator aperture, and it is difficult to quantitative estimate its impact.

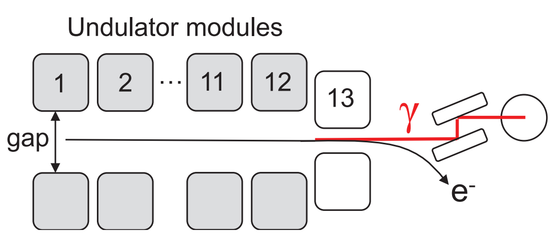

Figure 8: Measurement of the energy loss produced by the wakefield in the first 12 undulator units.

Making use of the correlation between photon energy and electron energy, it is possible to measure the losses produced by the wakefield during the machine commissioning. Starting with all undulators opened but the last one (the 13th), the intensity after the monochromator can be measured around the nominal K-value of the 13th, see Fig. 8. After defining this baseline, the gap of the first 12 undulators can be closed in steps while the intensity is recorded.

Two effects can be measured; the first is the shift of the blue edge due to energy losses and the second one a change in the blue edge slope due to the increase of the energy spread.

An estimation of the impact of the wakefield on the electron beam is very important in the commissioning phase where the lack of a lasing signal could make any optimization very difficult. When a lasing signal is established, it can be optimized empirically changing the taper value and/or trying different tapering schema.

CONCLUSION

A consistent set of measurements has been identified for the commissioning of the undulator in the machine. Electron and photon diagnostic are both key instruments in the proposed framework. Sometimes they are used to check the quality of the magnetic measurements like the BPMs versus field errors, sometimes they are used for redundancy like in the alignment procedure where both electron and photon diagnostic are implemented. In the last example, the two approaches are only similar and they might give different results in case the straightness of the trajectory inside a module is not within the tolerances. The complexity of the machine requires a high flexibility in the diagnostic tools to speed up the commissioning and to reach the designed parameters.

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