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Characterization of helical APPLE X undulators with 90 mm period for the European XFEL

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Abstract. European XFEL is going to provide full polarization control in the soft X-ray SASE line (SASE3). For this purpose, four helical APPLE X undulators with 90 mm period are installed downstream with respect to the planar undulators of the SASE3 undulator line consisting of 21 planar undulators with 68 mm period. In this contribution, the measurement technique, as well as the results of the measurements and tuning of the APPLE X undulators performed at European XFEL are presented.

1. Introduction

Four APPLE X undulators have been installed downstream with respect to the planar undulators of the soft x-ray line named SASE3 [1] at European XFEL. APPLE X undulator is a novel APPLE-type undulator, which has the flexibility to control symmetrically the radial and the longitudinal movement of all magnetic arrays. This feature provides full polarization control, including linear polarization with variable angles, elliptical polarization with variable phases, as well as other potential operational modes [2]. The planar undulators of the SASE line have the parameters of 68-mm undulator period and 1.66-T magnetic field. For the whole SASE3 undulator system, the photon energy produced by these APPLE X undulators should overlap with the one produced by the planar undulators. The period and magnetic field are therefore adapted from the original design at Paul Scherrer Institut (PSI) to 90 mm and 1.26 T [3]. The radial magnets with a dove-tail clamping part, which causes the fish-like shape of the magnets, were used for the UE90 undulators. The radial magnets have two radiuses, R_{in} , which is close to the undulator magnetic axis, and R_{out} , which is close to the clamping part. This shape of the magnets was invented while designing the prototype of the U38 APPLE X undulator for the SwissFEL [2]. The main parameters of these devices are also presented in Table 1.

Table 1. The design parameters of the APPLE X undulator

Undulator period length λ_u (mm)	90
Undulator magnetic length (mm)	1957.5
Full periods per undulator	20
Gap variation range g (mm)	12.5 – 31.6
Shift range of each quarter (mm)	-45 – 45



Permanent magnet material	NdFeB
Permanent magnet remanent field B_r (T)	1.26
Magnetic permeability of material μ_{\parallel} and μ_{\perp}	1.05 – 1.17
Inner radius of permanent magnet R_{in} (mm)	5.25
Outer radius of permanent magnet R_{out} (mm)	23.5
Minimum slit L_{slit} (mm)	4.4
Undulator parameter K_{eff} for circular mode (Gap variation only)	3.38 – 9.59
Maximum K_{eff} parameter for linear horizontal/vertical modes	9.59
Maximum K_{eff} parameter for linear 45° mode	6.76

2. Magnetic Measurement System Overview

For the characterization of the APPLE X undulators, the same magnetic measurements technique and equipment, as was used during the characterization of the APPLE X undulators for the Athos soft X-ray beamline at SwissFEL, was used [4,5]. The system contains the following main components: adjustable and longitudinally movable 3D Hall sensor, moving wire system, active Hall sensor position tracking and adjustment system based on two laser beams and two PSDs, two robots for the shimming of the magnets, five axes cam mover positioning system, Beckhoff, TwinCAT based control system.

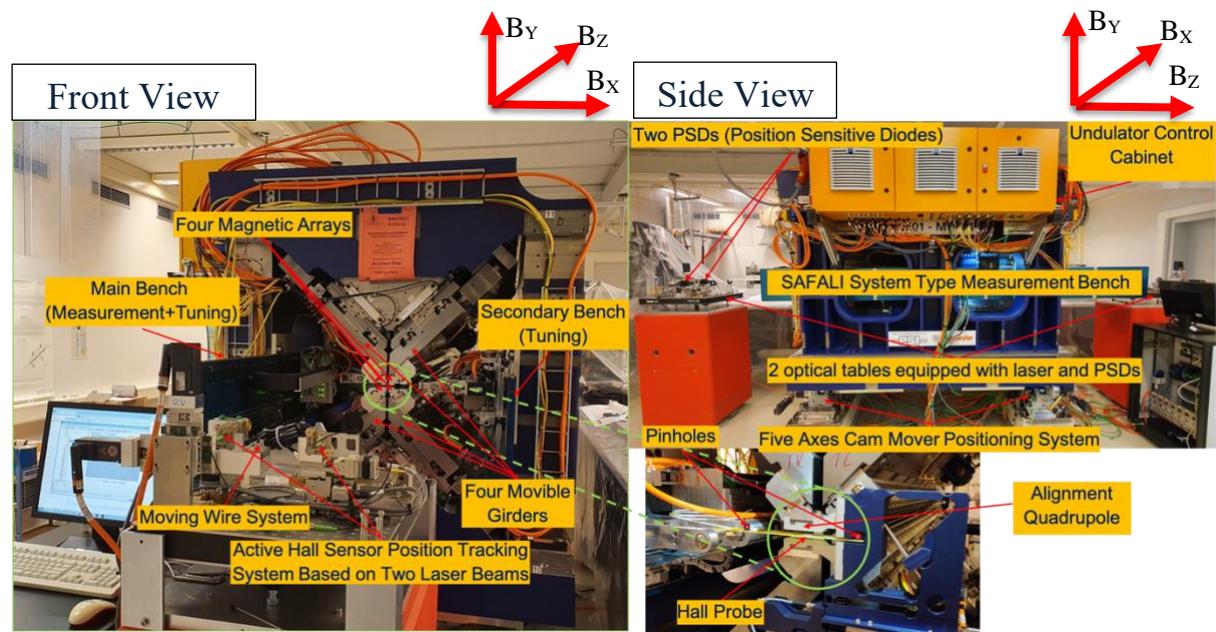


Figure 1. Overview of the measurement and calibration bench of the APPLE X undulator.

The magnetic measurements setup with the undulator is shown in Figure 1. It consists of a 3D Hall sensor (SENIS) movable along the magnetic axis combined with a moving wire system. A real-time position feedback control loop is implemented to keep the position of the Hall sensor along the magnetic field axis during a scan. The system is realized using the Self-Aligned Field Analyzer with Laser Instrumentation (SAFALI) system principle [6]. The main idea is to use two laser beams directed from the undulator downstream side towards the upstream side, passing through two pinholes installed on the Hall sensor holder equally separated on either side of the Hall sensor. Two position-sensitive detectors

(PSD) are installed on the undulator upstream side. Those detectors measure the intensity change of the laser beam in case the pinholes are shielding the laser beam. The Hall sensor guiding system interprets it as a slip-off from the optimal trajectory and sends the correction commands to the Hall sensor holder axes so that the intensity of the detected laser beam stays stable. The achieved positioning accuracy of the Hall sensor during its movement along the undulator is $\pm 25 \mu\text{m}$.

3. Magnetic Measurement Results

The specifications for the APPLE X undulator are shown in Table 2.

Table 2. Specifications for the UE90 Undulator

Parameter	Value	Unit
B_y RMS trajectory	≤ 210	Tmm^2
B_x RMS trajectory	≤ 210	Tmm^2
Entrance and exit B_y and B_x kicks	$\leq \pm 250$	μTm
Deflective local K at minimum gap LH, LV, C+, C-	≥ 9.0	
Deflective local K at minimum gap Linear 45°	≥ 6.5	
Combined field integrals of ambient magnetic field and magnet structures	$\leq \pm 1000$	μTm
RMS phase jitter	≤ 8	degree
Good field region Y direction	$\geq \pm 0.15$	mm
Good field region X direction	$\geq \pm 0.15$	mm

The experience of magnetic measurements showed that the total values of combined field integrals of ambient magnetic field and magnet structures should not exceed $\pm 1000 \mu\text{Tm}$. Based on this, it was decided to equip the vacuum chamber with a corrector, both in the horizontal and vertical directions, to compensate for those values. The plots presented in Figure 2 show that the specification is fulfilled for the GFR (good field region) values for the circular and LH polarization modes. The GFR is the region where the K value changes for the SASE3 by $\Delta K/K = 1 \cdot 10^{-3}$. The measurements showed that in the worst case, linearly polarized mode, the GFR lies in the range of $\pm 0.2 \text{ mm}$, which is larger than the required value of $\pm 0.15 \text{ mm}$.

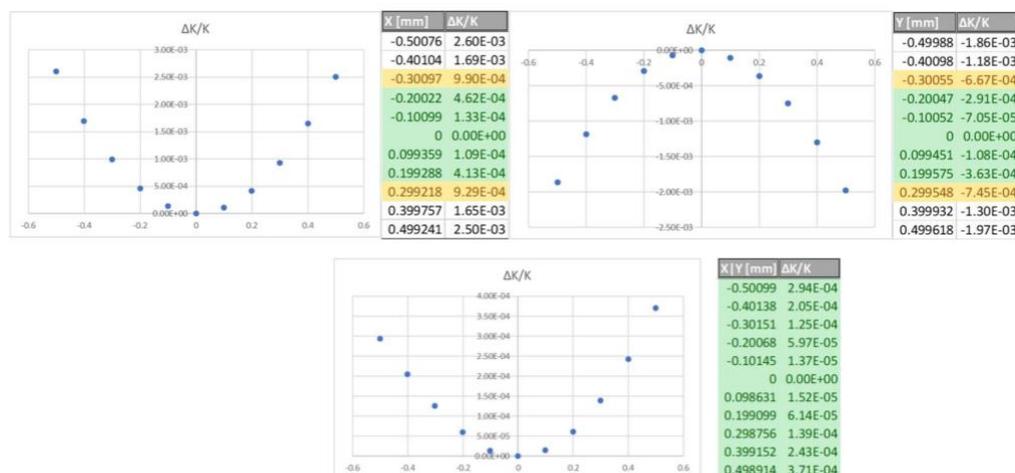


Figure 2. GFR in X and Y directions for LH mode (top plots) and the circular polarization mode (bottom plot)

An example of the measurements performed on one undulator is shown in Figure 3. In order to reach the small phase errors, as indicated in Figure 3 top right plot, several tuning iterations have been performed. All four devices were successfully fulfilling the specifications presented in Table 2. The K parameter and the phase error, as well as the remaining magnetic field integrals and the entrance and the exit kicks of B_Y and B_X components for the different polarization modes, are presented in Figure 3.

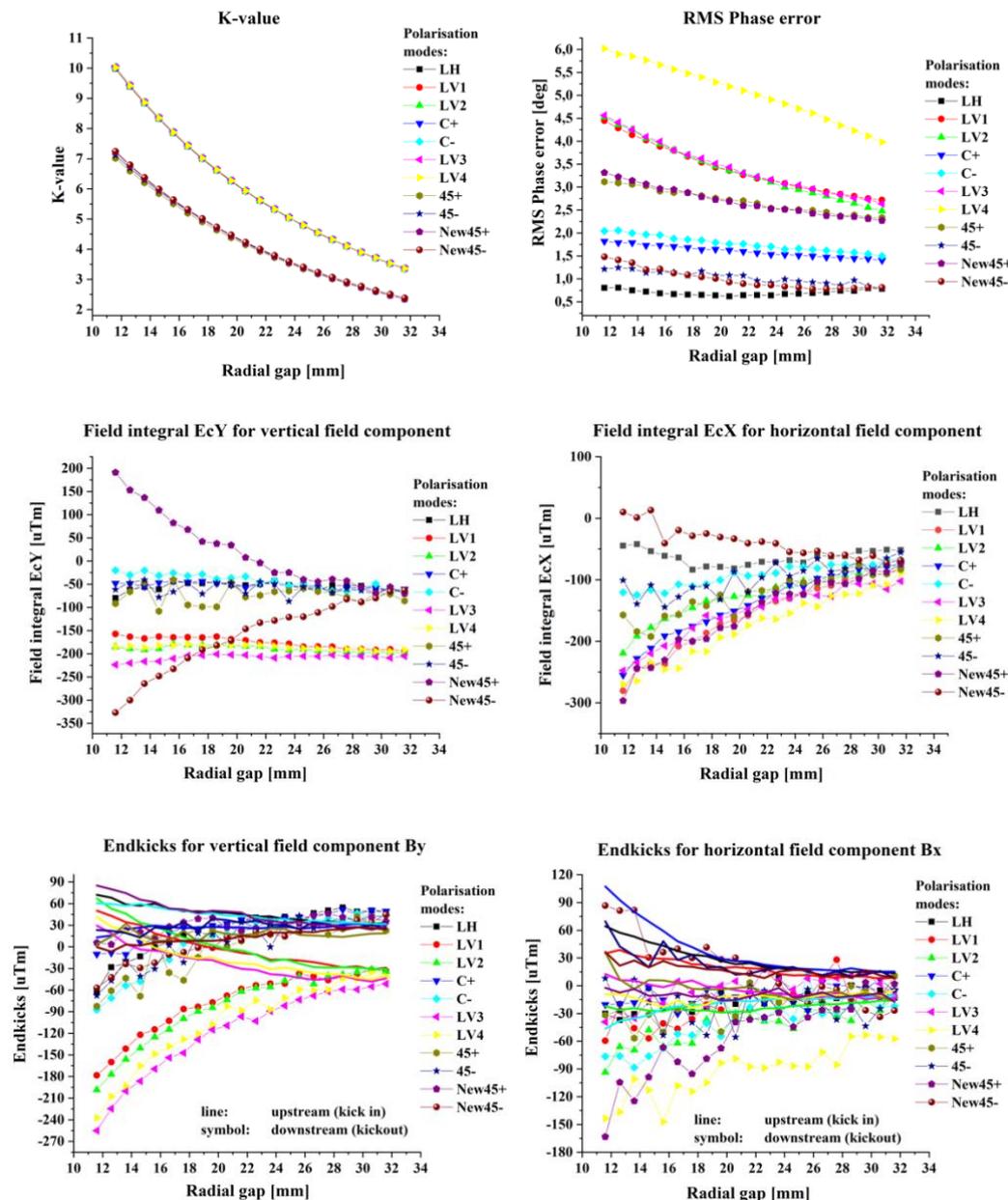


Figure 3. An example of the main magnetic measurement results of one U90 APPLE X undulator

All following modes: Linear Horizontal (LH), Linear Vertical (LV) (1,2,3,4 mean four extremes of the two different anti-parallel modes), Right-handed/Clockwise Circular (C+), Left handed/Anticlockwise Circular (C-), have the same K value, while the Linear polarization at +/- 45 deg (45+/-), Asymmetric Linear polarization at +/- 45 (New 45+/-) [2] modes have a smaller one, therefore

allowing for a smaller tunability of the photon energy. The top left plot presents the K values as a function of the gap for the different polarization modes. The K value for the minimum radial gap of 12.5 mm gap on the LH, LV C+, and C- is 10, which is required ≥ 9.0 ; for the Linear 45° modes, the requirement of the K value at the minimum gap to be ≥ 6.5 is also fulfilled.

An example of the magnets height error and the phase error values before and after the tuning of the magnets, excluding the end structures, is shown in Figure 4.

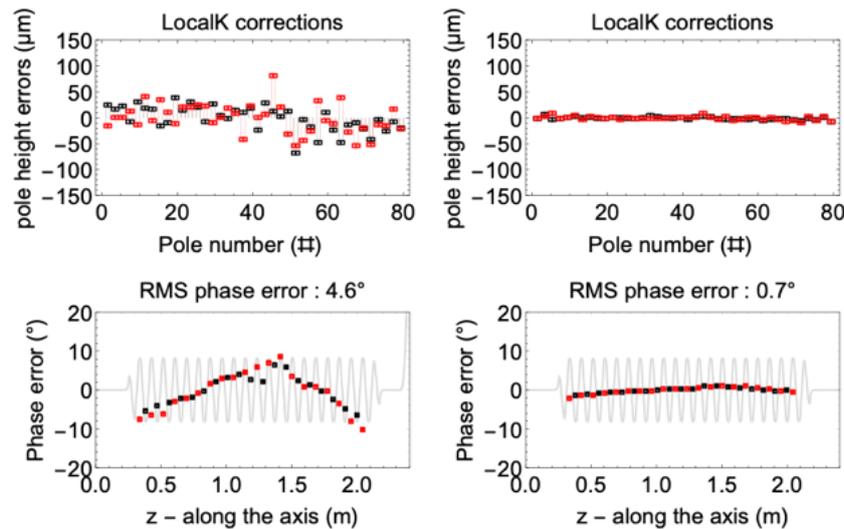


Figure 4. An example of the magnets height error and the phase error value before (left two plots) and after (right two plots) tuning of the main magnetic structure of the APPLE X undulator.

The end magnets tuning has been done manually for both vertical and horizontal entrance and exit kicks, while for the main magnetic structure, the tuning robots were used. An example of the B_y and B_x entrance and exit kicks before and after the tuning of the end magnetic structure is shown in Table 3.

Table 3. An example of the B_y and B_x entrance and exit kicks before and after the tuning of the end magnetic structure of the APPLE X undulator

Parameter	Before tuning the end magnetic structure (Tmm ²)	After tuning the end magnetic structure (Tmm ²)
Entrance B_y kick	-193.9	-0.35
Entrance B_x kick	295.2	-7.17
Exit B_y kick	384.2	-7.93
Exit B_x kick	96.5	0.95

4. Summary / Outlook

All four APPLE X undulators were successfully measured, tuned, and characterized within the specifications in the European XFEL magnetic measurement lab, using the SAFALI system type measurement bench and tuning robots designed and produced at PSI.

The APPLE X undulators were successfully installed downstream of the SASE 3 Soft X-ray planar undulator system during the winter shutdown of 2021. Currently, the commissioning of the installed undulators is ongoing.

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