TUNING AND TESTING OF THE PROTOTYPE UNDULATOR FOR THE EUROPEAN XFEL

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Abstract

The European X-ray Free Electron Laser (EXFEL) uses three undulator systems with a total magnetic length of 455 meters. There are 91 undulator segments each 5m long. They are gap variable use planar hybrid undulator technology. They are currently in production. During the next 2.5 years they will be measured and tuned so that their field complies with the EXFEL specifications.

In order to meet the tight schedule and to reach the high specifications, fast and reliable measurement methods and fine tuning algorithms have been developed and tested so that they can be used for the mass production. In this paper a short description is given. First results of the magnetic tuning preformed on some of the pre-series undulator prototypes, which were built during the past 18 months are given. It is shown that the field quality satisfies all the specifications of the European XFEL. It is also shown that the measurement and tuning process is fairly fast and straightforward to apply.

INTRODUCTION

The European XFEL is currently under construction [1]. It uses the principle of Self-Amplified-Spontaneous-Emission, (SASE), [2, 3]. Three systems will be built: SASE1 and SASE2 will operate in the hard X-ray regime from 0.05 to 0.2nm. SASE3 can be operated in the soft X-ray regime from 0.4 to 5.2 nm.

SASE FELs need long undulator systems: SASE1/2 will each use 35 segments and have a total length of 215m. SASE3 requires 21 segments comprising a total length of 128m. In total, 91 segments will be produced.

Due to the short wavelengths, the magnetic fields of the EXFEL undulator segments need to fulfil demanding specifications in order to provide longitudinal phase synchronization and transverse overlap over the whole length of an undulator system. Since the undulators are gap-tuneable the specifications must be fulfilled over the whole operational gap range. Tuning of the 91 undulator segments is a big challenge. The EXFEL time schedule requires all undulator segments to be finished by the end of 2014.

DESIGN AND SPECIFICATIONS

Two types of magnet structures will be used in EXFEL. The U40 with 40mm period length will be used for the hard X-Ray FELs SASE1 and SASE2. The U68 with a period length of 68 mm is used for the soft X-ray FEL SASE3. All undulator segments are planar hybrid devices using NdFeB magnet material and CoFe soft iron poles. Six so-called pre-series prototypes, four U40s and two U68s were built in 2011 to test the whole production cycle. All devices were tuned following the EXFEL procedures. Two representative devices, one U40 and one U68 are described here.

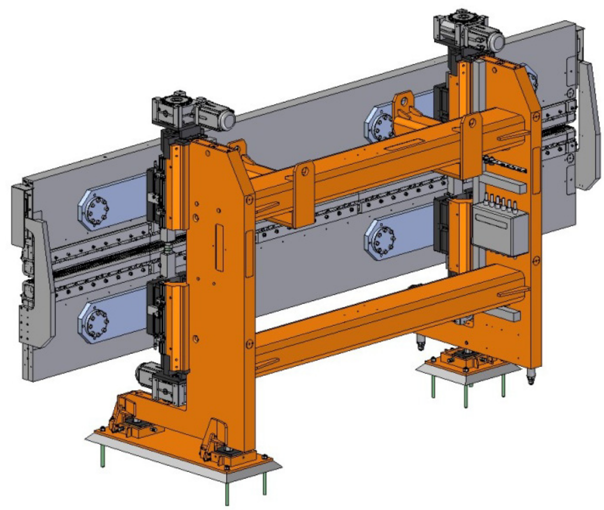

Figure 1: The EXFEL undulator.

All EXFEL magnetic structures have odd symmetry. The end structures have the configuration: ½, -1, 1, …,-1, 1, -½. The sign denotes to the orientation of the magnetization. Due to the opposite signs on the ends systematic gap dependent kicks are self-compensating. There is a small offset in the 2nd field integral, which is, however, below specifications, see Table 1. This configuration has a simple end design, maximizing the number of good poles, and in addition has low gap dependence.

A standardized mechanical support system is used throughout the EXFEL (see Fig. 1). It provides a standard mechanical interface to accommodate either a U40 or an U68 magnet structure. More details are found in [1].

The transverse e^--beam size of the EXFEL in the undulator sections is about 25 microns, smaller than that in storage rings. The required good field regime is therefore more moderate. In addition, e^--beam passes undulator only once in EXFEL. Consequently it makes a big difference to undulators used in storage rings.

For a radiation wavelength of 0.1nm and a normalized emittance of 1.4μm careful studies using Genesis 1.3 [4] have been made to establish tolerable magnetic field errors [5,6]. In these studies the phase jitter is used as a measure of the longitudinal matching of the micro-bunched electron beam with the laser field, and the transverse overlap is calculated to optimize the interaction. Tolerances were determined in such a way

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that the resulting loss in FEL power does not exceed 10%. Table 1 gives the tolerances that concluded from these studies [5, 6].

Table 1: The Specifications for EXFEL Undulators

1st Field Integral Error (Tmm)	Tolerable end End Kick (Tmm)	RMS 2nd field integral error (Tmm^2)	RMS Phase Jitter (degree)
±0.004	±0.1	116	8.5

The specifications listed in Table 1 have to be met over the operational gap range: 10-20mm for U40 and 10-23mm for the U68. The tolerable 1st field integral errors are too small for passive end correctors over the whole range of operational gaps. For high precision control of the entrance and exit angle of the electron trajectory, two pairs of horizontal/vertical air coils will be used on either end of the undulator. With the help of these coils the specifications on the magnet structures can be relaxed to a practical level of about ±0.1Tmm. Smaller values can be achieved by applying gap-dependent correction currents, which may be based either on magnetic measurement in the lab or later on in-situ measurements using beam based diagnostics. Small gap adjustment is straight forwardly implemented in the control system. The investigation in Ref. [6] shows that the RMS beam wander for SASE 1 should be smaller than 2µm, which corresponds to a RMS of the 2nd field integral smaller than 116 Tmm^2.

RESULTS OF MAGNETIC MEASUREMENTS

On delivery from the vendors an undulator segment does not yet fulfil the specifications listed in Table 1. After delivery and final assembly it needs to undergo magnetic measurement and tuning. It is measured on one of the three magnetic measurement benches, which have been set up for the tuning of the EXFEL undulator segments. They are identical and use the same hardware, software and techniques. For magnetic measurements all use hybrid sensors, a combination of a Hall-probe for the vertical field and a sensor coil with a large winding area for the horizontal field.

This hybrid probe is supported by a handle with 5 degrees of freedom, which is explained in more detail below. It is mounted on the platform of the bench, which is guided by air bearings and driven by a linear motor. This system provides a positioning accuracy ±1µm. The measured position jitter of the bench amounts to 2.3µm. The field accuracy measured by Hall probe is about 30µT. In order to increase accuracy an average over 5 scans is taken. Measurements are controlled by LabWindows control software [7].

First, the undulator needs to be aligned to the scanning axis of the bench using its adjustors and alignment screws. For the magnetic alignment the hybrid sensor scanning axis as determined by the bench is aligned to the undulator axis. This is done by scanning the field along the longitudinal (x-), vertical transverse (y-) and horizontal transverse (z-) direction. Transverse scans of By are performed at the pole locations.

The hybrid sensor is mounted on a goniometer head, which is supported by a 360° circle so that it can be rotated around the horizontal transverse direction. There are 5 degrees of freedom. They are used to align the hybrid sensor in such a way that its magnetic centre is kept unchanged when the probe is rotated between 0 and 180°. This allows for taking the difference of two Hall probe measurements done at 0° and 180°:

$$\bar{B} = \frac{B(0°)-B(180°)}{2}. \quad (1)$$

Taking this difference eliminates all non-linear contributions of even orders in the Hall probe calibration and thus allows for higher precision in the evaluation of field integrals. All Hall-probe data are treated this way.

For fine tuning of the fields the pole height tuning method already used for FLASH [8] has been refined [9]. Now in addition to pole height tuning, which changes the local gap the poles can be tilted by about ±4mrad. If top and bottom poles are tuned symmetrically by the same angle the vertical field stays unchanged, but the horizontal field component can be tuned. Also the poles near the ends, which in FLASH could not be tuned, are now tuneable. In principle at the reference gap all field errors can be tuned tolerance levels within on tuning step.

A tuning program has been developed to calculate the required shift and tilt for each pole based on two criteria: for the vertical field the local K parameter is kept constant for each half period. For the horizontal field the second field integral is kept at zero. Pole height and tilt adjustments can be superimposed, so that both tuning steps can be combined to single one.

Field Harmonics

Hybrid undulators usually show odd field harmonics, which increase if the ratio of undulator gap and period gets smaller. A Cos-function is used to fit the high harmonic coefficient:

$$B(z) = \sum_{n=1}^{\infty} A_n \cos\left(\frac{2n\pi}{\lambda_u} z\right), \quad (2)$$

where n is odd and denotes to the harmonic number and A_n is the amplitude of the n^{th} harmonic component. Table.2 lists the 1st, 3rd and 5th harmonics at gap 10mm and 12mm for the U40 and U68. It can be seen that for the longer period length the higher harmonics get stronger and they get weaker with increasing gap.

Table 2: Field Harmonics of U40 and U68 at 10 and 12mm Gap

Gap	10mm			12mm		
Harm.	1st	3rd	5th	1st	3rd	5th
U40	1.061	0.070	-0.001	0.890	0.042	-0.001
U68	1.425	0.228	0.020	1.277	0.168	0.011

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Final Status of U40

The undulator U40-X002-K002 is described here to demonstrate the tuning results for the U40s. The peak field as a function of gap is shown in Fig. 2. The inset in Fig. 2 gives the fitting parameters a, b, and c and their errors to the function:

$$B_{peak} = \exp[a + b\left(\frac{g}{\lambda_u}\right) + c(g/\lambda_u)^2] \,. \qquad (3)$$

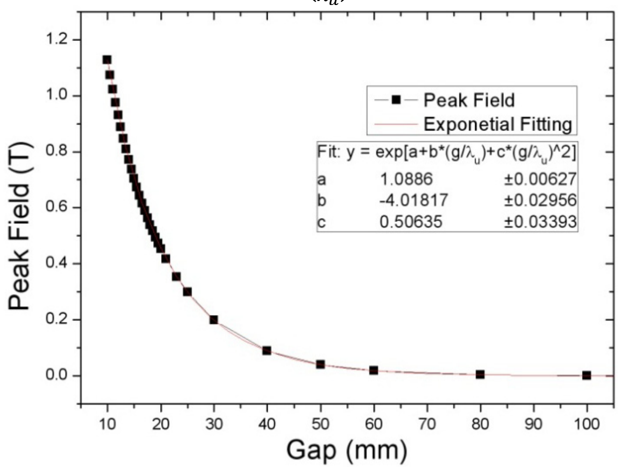

Figure 2: Peak field as function of the gap for the U40-X002-K002.

The K parameter and RMS phase jitter under different gaps are shown in Fig. 3. The working gap for the U40 is from 10 mm up to 20 mm. The K parameter varies from 3.96 to 1.31. The reference gap for fine tuning was chosen at 14mm approximately in the middle of the working gap range, in order to minimize the RMS phase jitter over the whole range. The local minimum at 14mm is only 1.5 degrees and the maximum excursion is 4.2 degree at 10mm. At the largest working gap, 20mm, the rms phase jitter is 2.7 degree. The RMS phase jitter fulfils the specification listed in Table.1 for all gaps.

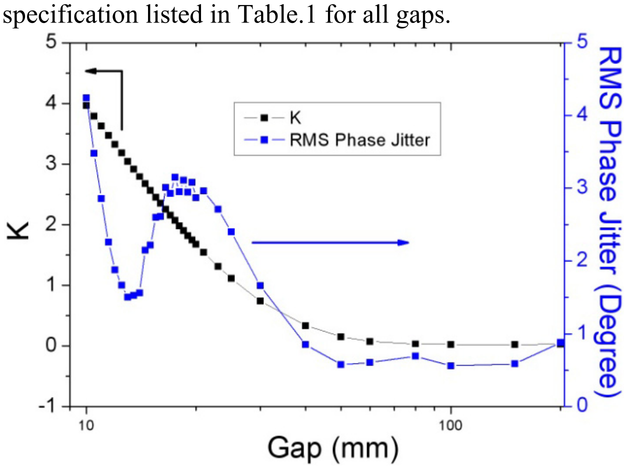

Figure 3: K parameter (black) and the RMS phase jitter (blue) of the undulator U40-X002-K002. The gap is shown on a logarithmic scale.

Figure 4 shows the second field integral for gaps of 10mm, 14mm, 18mm and 23mm. The corresponding RMS values are 36, 29, 39 and 32 Tmm^2, respectively. The entrance and exit kicks visible in Fig. 4 are illustrated in more detail in Fig. 5. Here, the entrance and exit kicks multiplied by -1 are shown as a function of gap. These are the corrections on vertical field, which need to be applied by the air coil correctors. They will be used on either end of an undulator segment. The required strengths are in the range of ±0.1Tmm.

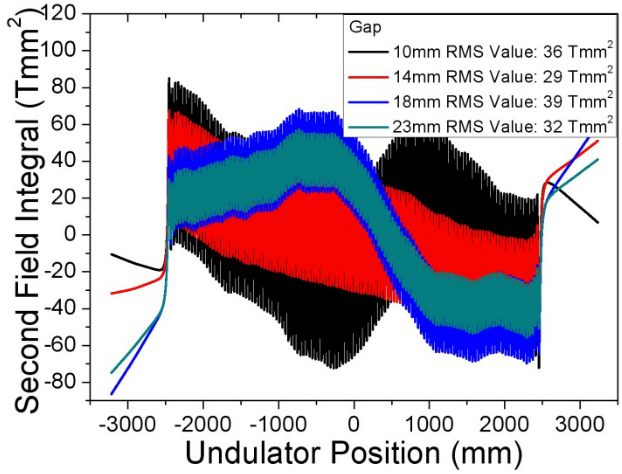

Figure 4: Second field integrals of U40-X002-K002 for four gaps.

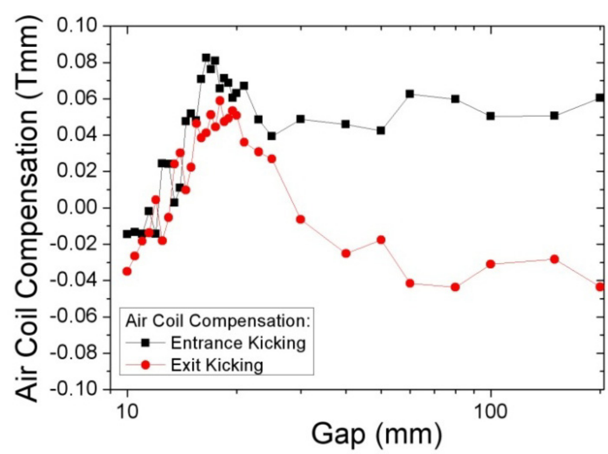

Figure 5: Compensation required by the air coil correctors for the undulator U40-X002-K002. The black squares are for the entrance coil and the red circles are for the exit coil.

Final Status of U68

The undulator U68-X003-N001 is described here as an example of the U68 devices. Due to the longer period the peak fields and K parameters are larger. The operational gap range of an U68 extends from 10mm to 23mm.

Figure 6 shows the peak field of U68-X003-N001 as a function of gap. The maximum peak reaches 1.66T at 10mm gap. The coefficients following Eq. (3) are given in the inset.

Figure 7 shows the K value and RMS phase jitter of U68-X003-N001. It is seen that the maximum K value reaches 9.06 at 10mm gap. The reference gap for tuning was again 14mm. Here the smallest RMS phase jitter is of 1.74°. At 10mm and 22 mm the jitter is 4.13° and 5.78°, respectively. The main influence on the gap dependent

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change of phase jitter is girder deformation by enormous magnetic forces of up to about 170kN. However it is shown by Fig. 8, that in the operational range it stays well within 6° the specifications.

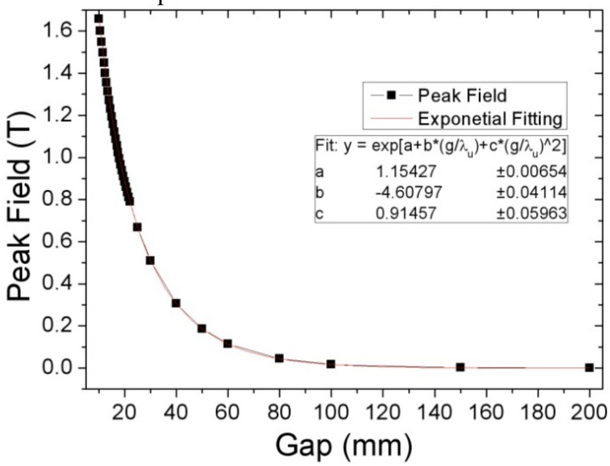

Figure 6: The peak field of U68-X003-N001 as a function of gap.

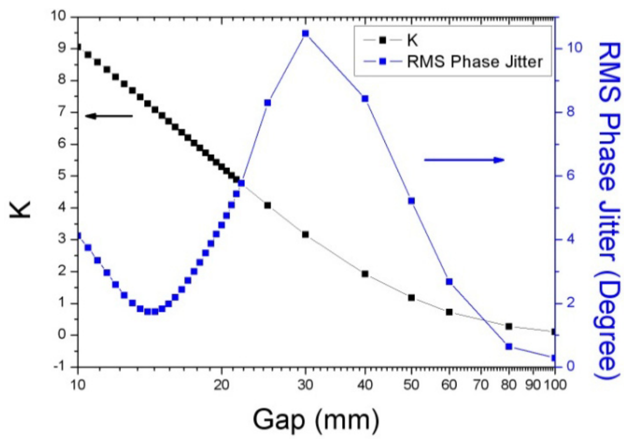

Figure 7: The K parameter (black) and the RMS phase jitter (blue) of the undulator U68-X003-N001. The gap is shown on a logarithmic scale.

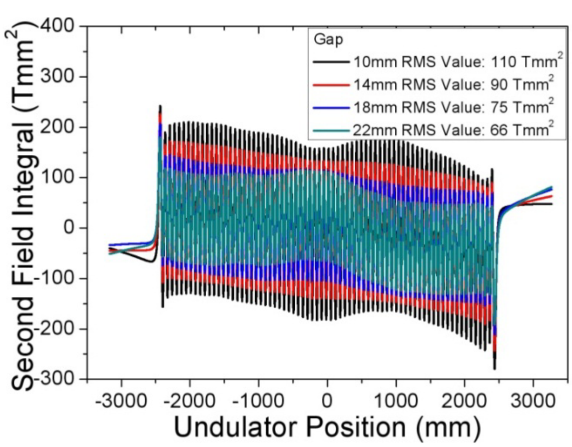

Figure 8: The second field integrals of U68-X003-N001 for four representative gaps.

The second field integral as a function of gap of U68-X003-N001 is shown in Fig. 8. The RMS values are 110, 90, 75, 66 Tmm^2. As can be seen in Fig. 8 the values mainly originate in the oscillation of the trajectory thereby trajectory errors are small.

Figure 9 illustrates the kicking compensation needed from the air coils on vertical field. It is seen that all values are within the specification ±0.1Tmm.

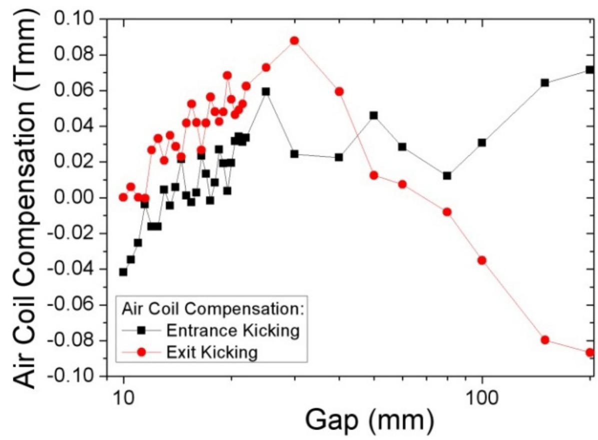

Figure 9: The compensation required from the air coils for the undulator U68-X003-N001. The black squares are for the entrance coil and the red circles are for the exit coil.

CONCLUSION

The European XFEL needs a large amount of undulator segments for the three SASE beam lines. Representative results of magnetic measurements made on two out of six pre-series devices are presented. Fast tuning and measuring procedure has been set up which results in good field qualities that fulfil the specifications for the hard x-ray FELs. Measurement systems and tuning algorithms are ready for the mass production of undulator segments.

ACKNOWLEGMENT

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