STATUS OF THE UNDULATOR SYSTEMS FOR THE EUROPEAN X-RAY FREE ELECTRON LASER

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Abstract

For the European X-ray Free Electron Laser (XFEL.EU) three undulator systems with a net magnetic length of 455 meters are planned, employing 91 undulator segments each 5m long. They are gap variable and use planar hybrid undulator technology. Their production has started in March 2012 using the technology and methods developed during the prototyping phase. An overview over the production and representative results are given.

INTRODUCTION

The European XFEL is currently under construction [1]. It uses the principle of Self-Amplified-Spontaneous-Emission, (SASE) [2, 3]. Three undulator systems will be built: SASE1 and SASE2 will operate mainly in the hard X-ray regime from 0.04 to 0.2 nm. SASE3 will be operated in the soft X-ray regime from 0.4 to 5.2 nm. Parameters are given in Table 1 below.

Table 1: Parameters of the XFEL.EU Undulator Systems

	SASE1/2	**SASE3**
λ_0 [mm]	40	68
Operational Gap Range [mm]	10-20	10-25
K-Range	3.9–1.65	9.0-4
Radiation Wavelength Range [nm]		
@ 17.5 GeV	0.147-0.040	1.22-0.27
@ 14.0 GeV	0.230-0.063	1.90-0.42
@ 8.5 GeV	0.625-0.171	5.17-1.15
# of Segments	35	21
System Length [m]	213.5	128.1

SASE FELs need long undulator systems: SASE1/2 will use each 35 segments of 40mm period length (U40). Including the intersections each has a total length of 215 m. SASE3 requires 21 segments of 68mm period length (U68), resulting in a total length of 128 m. In total, 91 undulator segments, 70 U40s and 21 U68s are needed.

Due to the short radiation 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 [4]. Production started in early 2012. The EXFEL time schedule requires all undulator segments to be finished by the end of 2014. An overview over the production in industry and the tuning methods applied at XFEL.EU is given.

HARDWARE & PRODUCTION ASPECTS

The mechanical design of the XFEL undulator segments was the result of a synergetic collaborative effort for the insertion devices for PETRAIII at DESY [5] on one side and for the XFEL.EU undulator segments on the other. There is a common basis for key technologies such as motion control, mechanical design, magnetic design, magnetic tuning and measurement techniques.

Mechanical Design

For the large number of undulator segments for the XFEL.EU strict standardization is essential to simplify the design effort and allow for an economic production and maintenance. As a consequence there is only one standard mechanical support system for both the U40 and U68. It is designed to meets all requirements, specifically it withstands magnetic forces for the U68 and simultaneously fulfils the higher accuracy requirements for the U40. There is a standard interface on the girder surfaces towards the gap side. Different magnet structures, using his interface can be attached via clamps. In Fig. 1 an undulator segment for SASE1 equipped with a U40 structure is shown. The same AlMg alloy for both the girders and the non-magnetic support structure is used to minimize thermal deformation and increase thermal stability. More details are given in [6].

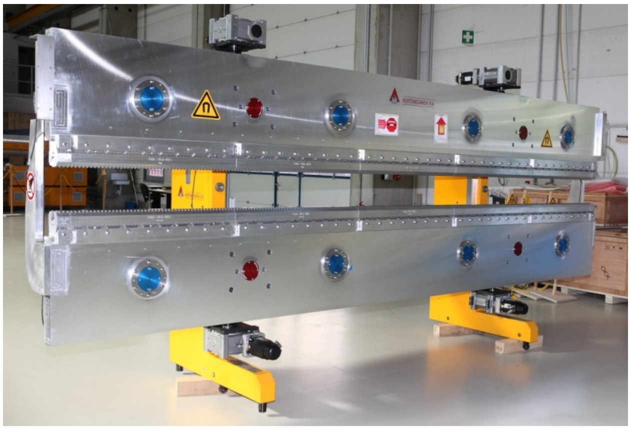

Figure 1: Undulator Segment for SASE1 with λ_0=40mm.

Motion Control System

Each undulator segment uses four individual servo motors to drive the gap. There are no coupling gears and drive shafts. Synchronization is done electronically by a

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local control system. It is based on industrial control and automation technology provided by Beckhoff GmbH and uses the EtherCAT fieldbus. More details are given in [7]. The magnetic gap is directly measured using absolute linear encoders on both ends as can be seen in Fig. 1. They measure the gap at the beam position with verified accuracy of ±1µm or better.

Industrial Production of Undulator Segments

Several prototypes were built in order to gain experience and optimize production. A very first prototype U40 was built together with IHEP, Beijing [8]. It helped to evaluate the design and verify that it is mature enough to start serial production.

Serial production for the XFEL.EU was organized in cooperation with European industry. It was found most economical to split the production into two main lots: The first includes the mechanical part assembled and ready for operation: Support frame, motors, spindles, guide rails, girders and the local control system. The second includes the magnetic structure, i.e. magnets, poles, non-magnetic support parts readily pre-assembled to be clamped onto the girders. The clamping is done after delivery to XFEL.EU and takes less than a day. This splitting allowed for economic manufacturing of undulator segments: Mechanical engineering companies were employed for the support structures while the magnetic structures were commissioned out to magnet suppliers with relevant experience in assembling magnetic systems.

Figure 2: The XFEL.EU Undulator Lab in Hall 36 in April 2013.

Large scale production was started in two steps. The first one included vendor qualification and selection and was started end of 2010. Six so-called pre-series prototypes were built for this purpose using different suppliers. After a final design review and revision of the drawings the production of the remaining 85 segments was launched in March 2012.

Magnetic Measurements and Tuning at XFEL.EU

After delivery there is the following work to be done at XFEL.EU: Clamping of the magnet structures to the girders of a support system, commissioning of the control system and finally magnetic measurement and tuning. A large experimental hall on the DESY site (Hall 36) with about 1100 m^2 of floor space became available for this work. Fig. 2 gives an impression: On the ceiling in rear the 20to crane is seen. About 3/4 of the area are needed for loading/unloading, assembling, various prototype setups, buffer storage space etc. This is seen to the left. About 1/4 of the hall space is occupied by three identical magnetic labs, the orange cabins seen in the middle left side. Each consists of a 10 by 6.5 m room temperature stabilized to ±0.1°C and contains a magnetic bench with 6.5 m travel.

The production cycle at XFEL.EU is best explained using Fig. 2: It starts with the delivery of hardware from suppliers through a gate on the left side end of the hall. Close by is the assembling area, where magnetic structured are clamped onto the support structures. After this step all poles are adjusted to a well-defined initial state with 0.5 mm pole overhang so that errors can be tuned by the procedure described below. After commissioning of the control system an undulator segment is ready for magnetic measurements. There is a storage area for these segments in the middle left of the hall. For magnetic measurements a segment is craned into one of the three magnetic labs through ports in their roofs.

The number of magnetic labs is a result of the XFEL.EU schedule: For undulator commissioning and tuning about two years in total are foreseen. Previous experience has shown that about three weeks are needed per undulator segment for craning into the hut, thermal adjustment, mechanic alignment to the bench, connecting the local control system and commissioning with the bench control system, magnetic measurements and tuning and finally referencing the magnetic axis to a number of laser fiducials attached on the frame. With three labs a production rate of about 1/week is feasible so that with some safety buffer the measurement and tuning can be done in two years.

The first serial segments arrived at XFEL.EU in Oct 2012 and were ready for measurements shortly after. Since then the processes were continuously improved and optimized resulting in a ramp-up of the production rate.

At present (August 2013) including the pre-series devices a total of 64 segments have been produced and arrived at XFEL.EU. Out of them 36 were measured and tuned and are ‘Ready for Installation’. Meanwhile one undulator segment per week is routinely completed.

The installation in the tunnels is planned to start beginning of 2015. In the meantime the majority of undulator segments are moved to an intermediate storage hall since the capacity of Hall 36 is limited to about 25-30 segments only.

Representative Magnetic Results

For the performance of the XFEL.EU the magnetic properties of individual undulator segments are of paramount importance.

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Table 2 shows the specifications. There are two comments, which need to be made: First, most specifications need to be fulfilled over the full operational gap range. In general properties such as Phase Jitter or RMS orbit excursion are to some extent gap dependent. In order to minimize this gap dependence tuning and error corrections are done at the tuning gap, see also below. It was empirically selected to minimize overall deviations.

Table 2: Magnetic specifications for XFEL.EU undulator segments

Property	U40	U68
Operational Gap range [mm]	10 – 20	10 – 25
Period Length [mm]	40	68
Tuning gap [mm]	14	16
B_y RMS trajectory [Tmm^2]	≤ 100	≤ 210
B_x RMS trajectory [Tmm^2]	≤ 70	≤ 70
Entrance and exit B_y and B_x kicks [Tmm]	|≤ 0.15|	|≤0.15|
B_y and B_x kicks at tuning Gap [Tmm]	≈ 0	≈ 0
Max. K at gap=10mm	≥ 3.9	≥ 9.0
RMS Phase Jitter all Gaps [Degree]	≤ 8	≤ 8
RMS Phase Jitter @ tuning Gap [Degree]	≤ 2.5	≤ 2.5

Second, the tolerance on the entrance and exit kicks apply to the static permanent magnet properties only and therefore are more generous as compared to the specs for the FEL process [4]. In addition there will be one horizontal/vertical Air Coil Corrector (ACC) on either end of an undulator segment, with sufficient strength to compensate kick errors with high accuracy. In this way requirements for gap dependent kicks induced by the permanent magnet structure can be kept on a reasonable level. Moreover gap dependent excitations of the ACCs can be applied and thus allow for exact compensation of the total first and second horizontal and vertical field integrals of an undulator segment at any gap.

Magnetic measurements and tuning follow closely the procedures developed for the pre-series prototypes: A 2D-Hybrid sensor is used, which combines a commercial Bell-Sypris 7010 Hall-Probe for the vertical B_y field and a sensor coil with a winding area of about 0.25 m^2 together with an analog integrator for horizontal B_x field. For definition of coordinates see Fig.3. The accuracy of the Hall data is increased by taking the average of two measurements, one with the Hall probe at 0° and one at 180° reversing the B_y with respect to the probe. The resulting field is given by: $\bar{B}_Y = 0.5(B_y(0°) - B_y(180°)$. In this way the unsymmetry $B_y \rightarrow -B_y$ is eliminated, which is observed even on well calibrated systems. More details are given in [6].

An undulator segment is aligned so that probe axis and magnetic axis on average coincide vertically by <±10 µm and horizontally to ±10-20 µm.

For horizontal and vertical field tuning all poles of a XFEL.EU undulator segment can be height adjusted by ±300 µm and tilted by ±4 mrad, see Fig. 3. In this way field errors are tuned just by using the adjustment screws. No shims are needed. For radiation properties the vertical field is most important. A slight modification of the Pole Height Adjustment described in ref [9] was used:
From the measured on axis field distribution $B_y(z)$ along the beam axis, z, the local K-Parameter of a pole with index j, K_j, is defined by:

$$K_j = \frac{e}{mc}\int_{z_j-\frac{\lambda_0}{4}}^{z_j+\frac{\lambda_0}{4}} B_y(z)dz \qquad (1)$$

Here y is the direction of the main field component. e, m and c are the electron charge, mass and speed of light, respectively. λ_0 is the undulator period length and z_j the position of the j^{th} pole. K_j is proportional to the area under a pole at $z_j \pm\lambda_0/4$ i.e. between the adjacent zero crossings of the field. By using the method of ref. [9] the pole height adjustments for all poles required to tune the errors are found. Fig. 4 gives a demonstration for a U68. The local K_j of the full poles, i.e. excluding the ends are plotted in Fig. 4, left, as a function of the pole number j for the tuning gap of 16mm. It is seen that initially there is a parabola shaped profile resulting from some mechanical deformation together with a large scatter. After only one tuning step all K_j are nearly constant and the scatter is drastically reduced. Fig.4 right shows the corresponding Phase Errors on the poles along the undulator. The RMS Phase Jitter is reduced from initially 15.6° by one pole tuning step to only 2.1°, which is well within specs.

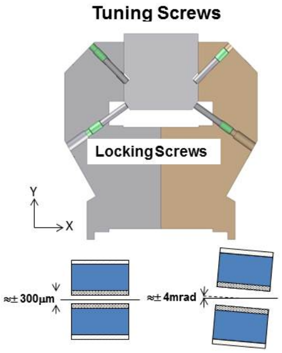

Figure 3: Pole height and tilt adjustment principle.

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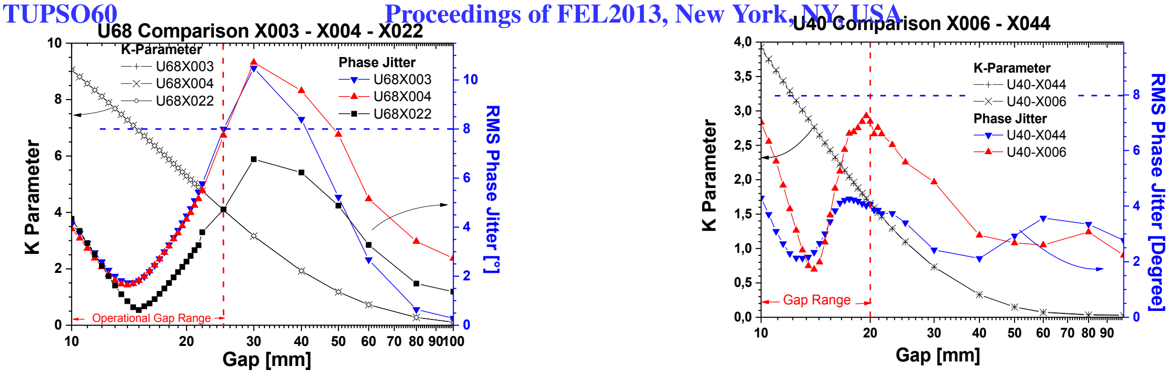

Figure 5: Representative gap dependences of three U68's, left and two U40's, right. The K-parameters, shown by the crossed symbols agree for different structures. The Phase Jitters, shown by the full symbols may vary from device to device but stay within specs. Operational gap range and tolerance limits are shown by the dashed lines. The horizontal axis is logarithmic to emphasize the operational gap range.

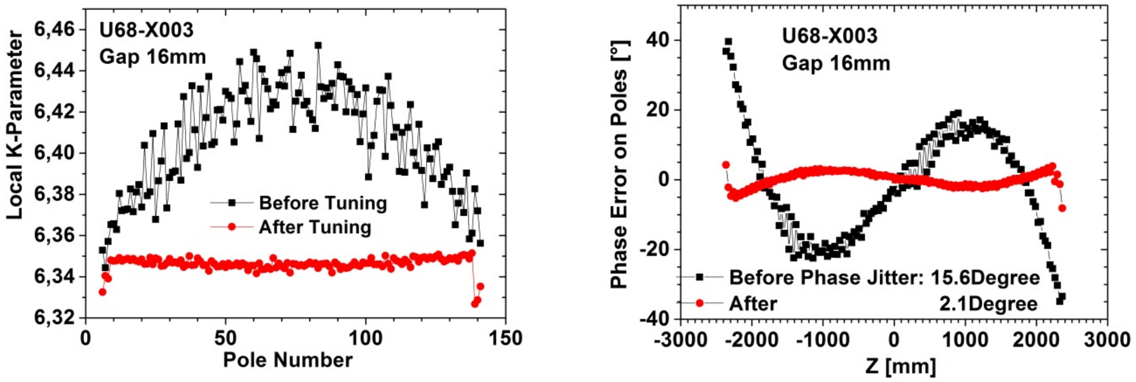

Figure 4: Demonstration of the local K-tuning, left and the effect on the Phase Error on the poles, right.

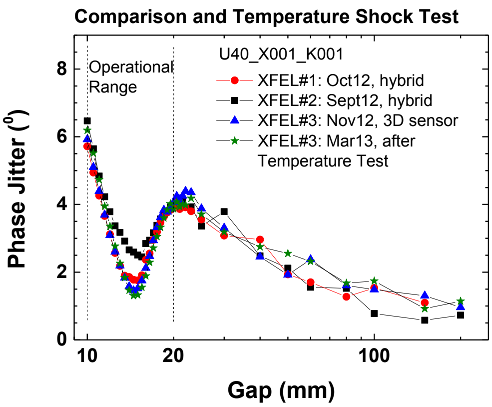

Figure 6: Phase Jitter of X001 as measured in the tree labs and after temperature shock test.

Figure 5 gives a representative overview over the gap dependence of the Phase Jitter and the (integral) K- Parameter for three U68s and two U40s. Production numbers ≤ X006 refer to the pre-serial and the others to the serial production. It is seen that the K-Parameter for both structures agree very well. The Phase Jitter as a function of gap, however, varies for different structures. It always has pronounced dips at the tuning gaps but gets larger to either side. The gap dependence is dominated by mechanic deformation of the girders. The reason for the differences is not yet fully understood. However, the observation is: 1.) The Phase Jitter is within specs for all gaps and 2.) the variation was larger at the beginning of the production and is getting smaller with increasing production experience.

The Phase Jitter is a key figure of merit for the FEL process. In order to test the accuracy of the measurements Fig. 6 shows the Phase Jitter of one U40 structure, X001, as measured in the three different labs XFEL#1 through #3. It is seen that measurements in all labs agree on average better than 0.5 degree and are well within specifications. The green stars in Fig. 4 represent the result of a 72 hours temperature shock test: Starting at RT the X001 was exposed to temperatures as low as 2°C and then warmed up again to RT and re-measured in XFEL#3. The comparison of data before (blue triangles) and after (green stars) shows no significant difference. This demonstrates, that the design is quite robust to temperature exposure.

CONCLUSION

The large scale serial production of the undulator segments for the European XFEL is in full swing. After some ramp up time the planned production rate of about one undulator segment per week is reached. By August 2013 about 36 devices were measured and tuned and prepared 'Ready for Installation'. This is well within the XFEL.EU production schedule. Magnetic measurement results show, that all specifications can be met reliably although some fluctuations are observed. Fluctuations were larger at production start and are getting smaller with increasing production experience.

REFERENCES

[1] M. Altarelli et al., The European X-ray Free Electron Laser, Technical Design Report, ISBN 3-935702-17-5, 2006. http://www.xfel.eu/dokumente/technical_documents

[2] H. Kondratenko and E. L. Saldin, Part. Accel. 10. 207 (1980).

[3] R. Bonifacio, C. Pellegrini, and L. M. Narducci, Opt. Commun. 50, 373 (1984).

[4] Y. Li, B. Faatz, and J. Pflueger, Phys. Rev. Spec. Top. AB 11, 100701 (2008).

[5] M. Barthelmess, U. Englisch, J. Pflüger, A. Schöps, J. Skupin, M. Tischer, Contribution WEPC133, European Particle Accelerator Conference June 23-27, 2008, Genova, Italy

[6] U. Englisch, Y. Li, J. Pflueger, Contribution THPD18, Proceedings of the FEL2012, Nara, Japan

[7] S. Karabekyan, R. Pannier, J. Pflueger, N. Burandt, J. Kuhn, A. Schoeps, Contribution MOPMU012, ICALEPCS2011, 10-14 Oct, 2011, Grenoble, France

[8] H.Lu , W.Chen, M.Wang, S.Sun, Y. Yang, Z.Wang, X.Feng, C.Shi, X.Jiang, Y. Li, J. Pflueger, Contribution WEPB18, FEL2011, Shanghai, China

[9] J. Pflüger, H.Lu, T. Teichmann, NIM A429, (1999), 396

ISBN 978-3-95450-126-7