DEVELOPMENT OF THE FIRST U48 UNDULATOR PROTOTYPE FOR THE EUROPEAN X-RAY FREE ELECTRON LASER*

H.H.Lu#, W.Chen, M.T.Wang, S.C.Sun, Y. F. Yang, Z.X.Wang, X.Feng, C.T.Shi, X.M.Jiang
Institute of High Energy Physics (IHEP), Chinese Academy of Sciences (CAS)
19B Yuquanlu Road, Shijingshan District, Beijing 100049, CHINA
Y. H. Li, J. Pflueger
European XFEL GmbH, Notkestr 85, 22607 Hamburg, Germany

Abstract

The European XFEL (EXFEL) will be a user facility. In the startup configuration it will consist of three beam lines named SASE1, SASE2 and SASE3. For the SASE2 beam line a first undulator prototype called U48 has been developed and tested in a collaboration between the Institute of High Energy Physics (IHEP), CAS, China and EXFEL. It is 5-meter-long and the longest one ever developed and built successfully in China. Its weight is 8-tons. This contribution describes its design and specifications, dedicated R&D activities especially on the magnet material, mechanical design issues, the control system and the mechanical assembly. Finally results of magnetic measurements and tuning are presented.

INTRODUCTION

The startup configuration of the European X-Ray Free Electron Laser (EXFEL) will comprise three beam lines named SASE1; SASE2 and SASE3 and will be a user facility covering the wavelength range from below 0.1 to 1.6 nm [1] with a 17.5 GeV beam.

The undulator technology for the EXFEL has been developed at DESY, Hamburg in a synergetic R&D activity between the PETRAIII project and EXFEL since 2005. Various devices were built during 2007-2010 for PETRAIII using this technology and leading to a rich experience with the mechanical design, manufacturing techniques, magnetic materials, magnetic measurements and tuning techniques as well as with the motion control technology.

The undulators for EXFEL will be 5-meter-long. They are separated into three main parts: The mechanical support structure, the motion control system and the magnetic structure. This arrangement makes the undulators for the EXFEL a unique combination of permanent magnet technology, precision mechanical engineering and forefront control technology. As a part of the preparation for serial production one U48 Pre-Series Prototype for the SASE2 beam line for the EXFEL was built by IHEP, China.

This paper concentrates on the U48 development and test results, the magnetic design and requirements will be briefly introduced.

*Work supported by 973 Program 2008CB817703
#luhh@ihep.ac.cn

DESIGN ISSUES

In this section, an overview of design considerations, parameters choices and specifications is given.

Choice of Parameters

The main parameters for the U48 for the EXFEL SASE2 beam line are summarized in Table 1, [1]. The magnetic design was developed and optimized by DESY/EXFEL [2]. The dimensions of standard magnets and poles are 70×60×16.6 mm^3 and 50×50×7.32 mm^3, respectively. This design maximizes the peak field and minimizes field roll-off and stray fields. The end sections are designed for minimum gap dependence of the first field integral. The maximum design field is about 1.37 T at a gap of 10 mm.

Table 1: Parameters for the SASE2 Undulator U48

	λ_{Rad} [nm]	λ_u [mm]	gap [mm]	B_{max} [T]	K	β [m]	L_{sat} [m]
SASE2	0.1	48	19	0.63	2.8	45	174
	0.4		10	1.37	6.1	15	72

Simulation and Tolerance

Undulator tolerances are determined by FEL physics. The line width of FEL radiation is given by the so-called Pierce parameter ρ, which for the XFEL amounts to 3×10^{-4} at 1Å. For a first estimate it can be used for specifications of girder deformation, accuracy of gap control, alignment, temperature stability, but also for the gap dependency of the first field integral and the phase shake. First estimates using this approach were given in [1]. For further refinement and better understanding the code Genesis 1.3 [3] was used to do FEL simulations and a field error analysis [4-6]. These calculations resulted in a relaxation of tolerance requirements as compared to Ref. [1] leading to a technical sound and economic solution. Table 2 gives a brief overview on the relaxed tolerances. They are well within present state of the art of technology.

ISBN 978-3-95450-117-5

Table 2: U48 Tolerance Requirements

Temperature Stability (One segment)	±0.1 K
Alignment (Each Segment)	±100 µm
Gap Control Accuracy (One Segment)	±1 µm
Flatness Change under changing magnetic forces	±10 µm

A substantial rectangular cross section of 500 by 100 mm^2 was used for the girders to minimize total deformation. A fourfold support of the girders in equidistant points was used to reduce the deformation under magnetic load dramatically. Magnetic support structures were clamped onto the girders. Identical material, an AlMg alloy, was used for the girders and all non-magnetic support parts of the magnet structure in order to avoid any differential expansion and resulting bimetallic deformation. Four motors were used, which are electronically synchronized by the motion control system.

DEVELOPMENT

U48 prototype development at IHEP, CHINA was on-going since 2007. The mechanical strength and deformation for the first generation prototype were re-analysed using ANSYS and the magnetic properties were studied using RADIA. After design release, vendors were qualified for the production of the magnet material and the mechanical structure. A two period model and jigs were built to test the machinery and the production techniques. Serial production of magnets and poles and the fabrication of mechanical structure were started in 2009. Some details are given below.

Magnetic Material

The magnetic material is one of the key components for an undulator. At the beginning of this project there was a big gap between the properties of available Chinese material and EXFEL requirements.

Within a dedicated R&D effort several sample magnets were produced and investigated. Finally a small batch of 50 magnets sufficient for one 0.9 m long magnet module was produced as an advanced test for the production. Based on this experience assembly techniques and procedures, quality rules, test procedures, acceptance tests etc. were established.

Table 3: Comparison of Magnets Quality

	EXFEL Specification	Before U48 Development	U48
Magnetization Errors **North South Effect**	<±1%	<±4%	<±2%
Angular Error	<±0.5°	<±3°	<±0.5°
Geometrical tolerance	±20-50 µm	±100 µm	±10-40 µm

Table 3 gives the comparison of the properties of Chinese magnets before and after research. It is seen that there is a significant improvement of the quality of Chinese material and EXFEL specifications are almost reached.

Mechanical Manufacturing

Mechanical manufacturing of the U48 includes the C-frame, the 5-meter-long girders and comb-like support structures.

The comb-like structures provide the supports for magnets and poles. They include a large number of threads for worm screws which act onto notches in the magnets and poles. Their proper working is essential for the pole height tuning to work reliably. A first a 0.9 m long module of a comb-like structure was built. Here production techniques, CNC programs, jigs could be tested and established. It was also a first experience with the magnetic assembly and tuning and the labelling and lettering conventions of poles and magnets.

The girders are the support structure for the comb-like structures. A standard interface using clamps is adopted. They have quite high accuracy requirements. Tests were made using girders made of domestic and imported AlMg alloy. Key procedures such as rough machining, natural aging, heat treatment and precise machining and achievable accuracy were established and controlled strictly. Finally, the girders for the U48 were made using AlMg profiles imported from USA.

The C-frame is a welded structure made of standard steel. Its size is approximately 2.7×2×1.2 m^3. For ultimate accuracy two steps were applied: First, stress release annealing of the whole frame at about 650 °C was done after welding. Second a suitable sized milling machine was used to do all machining steps in one setting. Both steps were repeated if needed.

Assembly

The assembly of the U48 required the following steps: First, the C-frame was pre-assembled including guidings, spindles etc. Then the girders were attached. Second, the 10 comb like structures needed for the U48 were preassembled and magnets and poles were inserted. Third, the magnet structures were attached to the girders. Five 0.9 m modules were clamped onto the upper girder and in the same way five modules were clamped on the lower girder. Special jigs were used to ascertain proper mounting and positioning. Finally the four end modules were mounted. For the start configuration for the magnetic measurements all poles were adjusted to have a 0.5 mm overhang over the magnets.

Commissioning of the Control system

The control system is based on components used for industrial process control and is made by Beckhoff, GmbH, Germany. For full compatibility a standard control system was developed for the undulator segments for the EXFEL [7]. It is readily supplied by the manufacturer. It is a fast, accurate and reliable system.

ISBN 978-3-95450-117-5

Synchronized motion of the four motors of an undulator segment with high precision can be realized. The off-line and on-line commissioning of this system was carried out. The components related to the control system, such as motors, gearboxes, limit switches, control cabinet were checked, configured and adjusted.

RESULTS AND DISCUSSION

After production and assembly, the acceptance test of mechanical and magnetic inspection was carried out.

Mechanical Acceptance Test

Mechanical acceptance test verifies the mechanical accuracy and alignment. It sub-divides into two parts, the alignment of the C-frame and the adjustment of the girders. All tests were done using a laser tracker.

Table 4 shows the specifications and the test results. As an example Figure 1 shows the change of the tilt of the bottom magnet girder for different gaps corresponding to different magnet forces. Data showed that the specifications at working gap range were fulfilled.

Table 4: Mechanical Acceptance Test @ gap=10-200mm

Specification		Test Result
Undulator Frame Alignment		
Permissible Angular Deviation	≤ ± 20μrad	≤ ± 20μrad
Alignment Tolerances of the Holders		
Tilt of a Magnet Girder with Magnet Structure	± 0.20mrad	Upper Girder [-0.3mrad,+0.20mrad] lower girder < ± 0.20mrad
Longitudinal Offset	± 0.1mm	< ± 0.1mm
Transverse Offset	± 0.2mm	< ± 0.2mm

Magnetic Measurements

All magnetic measurements were made using the new 8 m bench at IHEP built for the EXFEL undulator development. Its maximum effective travel distance is 6.5 m. The vertical BY field is measured using a Hall probe with a sensitive area of about 1 mm in diameter. It was calibrated against an NMR probe at the DESY magnetic measurement lab. The residual error of the calibration was about 2×10-5 T. The horizontal field BX was measured using a sensor coil of dimensions 3.95×13.55×7.0 mm3 with 7000 turns and a calibrated winding area of about 0.27 m2. A Lakeshore 480 analog integrator was used to integrate the induced voltage of the coil. Measurements were taken 'On the Fly' at a speed of typically 100 mm/s. Typical intervals of measurement were 0.5 mm and equidistant data point were taken. Field integrals and phase shake were calculated by numerical integration of these field scans. The details of bench are described in [8].

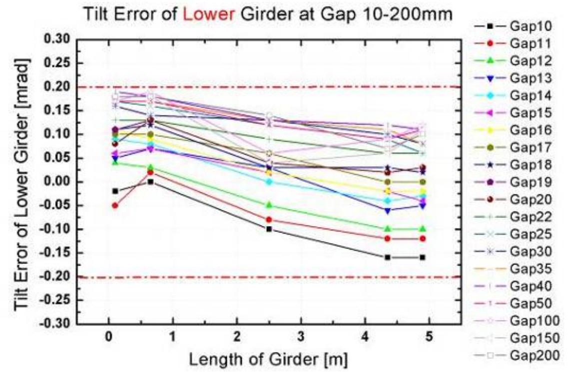

Figure 1: Typical result of tilt the bottom girder at different gaps respectively magnetic forces.

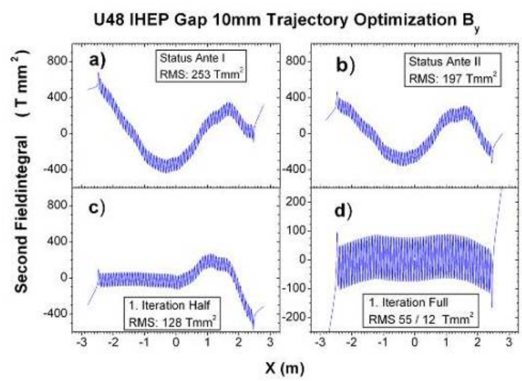

Figure 2: Results comparison of pole tuning on trajectory optimization.

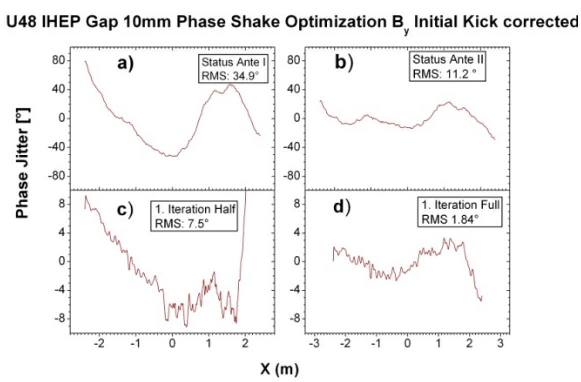

Figure 3: Results comparison of pole tuning on Phase Shake optimization.

Field errors were controlled in different ways: For assembly magnets were sorted using simulated annealing. The magnetic moments measured for each magnet in a Helmholtz coil were taken as an input. This provides some basic but not sufficient field quality. For ultimate error compensation pole height tuning was applied [9]. In order to compensate local field errors all poles can be shifted in and out by ±100 μm and tilted by ±4 mrad. This is quite effective for field error correction. Figure 2 shows the effect of pole height tuning on the B_Y field and the resulting 2nd field integral. For the EXFEL about 58 Tmm^2 correspond to a trajectory excursion of 1 μm. Figure 2 a), b) show two different measurements before tuning, c) shows the status after tuning half of the structure and d) when it was completed. Note the change of scale! Only one tuning step was sufficient. Figure 3 shows analogous results for the Phase Shake for the same steps as in Figure 2. The residual RMS Phase Shake after one tuning step is only 1.84°. Figures 2 and 3 demonstrate the potential of the pole height tuning method: The trajectory and Phase Shake can be optimized in only one step and brought to quite low tolerances without applying any shims.

Horizontal field errors are tuned by tilting the poles. Compensation works as effectively as was demonstrated in Fig. 2.

Table 5 shows the results together with the specs for the EXFEL covering the operational gap range for SASE2 from 10 to 19 mm. Here some compromises were needed to fully stay within specs for all gaps. Therefore the 10 mm values differ from Fig. 2 and 3.

Table 5: Magnetic Acceptance Test

	EXFEL Specification		**IHEP Magnetic Measurement Result**	
Vertical Field B_Y				
Gap	10 mm	19 mm	10 mm	19 mm
K_{ave} Value	6.1	2.8	6.3	3.0
Peak Field	1.37 T	0.63 T	1.40 T	0.68 T
1st Field Integral (at Exit)	$< \pm$ 0.2 Tmm		$< \pm$ 0.18 Tmm	
2nd Field Integral (RMS)	< 50 Tmm^2		< 40 Tmm^2	
Phase Shake (RMS)	< 6 °		< 5 °	
Horizontal Field B_X				
1st Field Integral (at Exit)	$< \pm$ 0.2 Tmm		$< \pm$ 0.02 Tmm	
2nd Field Integral (RMS)	< 50 Tmm^2		< 10 Tmm^2	

Figure 4: Photo of U48 after development.

All magnetic measurement results were within the required specifications. Peak field and K-Parameter exceed the requirements slightly. This confirms that mechanical and magnetic specifications are fulfilled. Figure 4 is a photo of U48 after development.

After the measurements and acceptance test the U48 was shipped to EXFEL in Hamburg, Germany and arrived on April 1, 2011. It is the first dedicated Pre-Series Prototype for the EXFEL. Presently it is being re-examined and measured.

SUMMARY

For the SASE beam line at the EXFEL a U48 prototype has been built and tested by IHEP, China. The progress with the quality of Chinese magnetic material was demonstrated. The mechanical and magnetic acceptance tests show that the quality of U48 prototype reached the EXFEL specifications.

This undulator prototype is the longest one built so far in China, at the same time it was the first undulator prototype completed for EXFEL and provided valuable information for the construction of the EXFEL undulator system development.

ACKNOWLEDGEMENTS

The authors would like to thank colleagues from Beijing Zhong Ke San Huan High-Tech Co., Ltd. for magnetic material improvement and the colleagues from the Accelerator Center and Workshop at IHEP as well as the Workshop at the Institute of Plasma Physics (IPP), CAS for continuous support in the process of U48 development.

REFERENCES

[1] M. Altarelli, Editor, The European X-Ray Free Electron Laser Technical Design Report, ISBN 3-935702-17-5.
[2] M. Barthelmess, Bulk Optimization of Undulator U48, Internal Technical Report.
[3] S. Reiche, Nucl. Instr. and Meth. A429 (1999) 243-248.
[4] Y. Li, B. Faatz, J. Pflueger, Physical Review Special Topics - Accelerator and Beams 11, 100701 (2008).
[5] Y. Li, B. Faatz and J. Pflueger, Proceeding of FEL 2007, Novosibirsk, Russia, P330.
[6] Y. Li, B. Faatz and J. Pflueger, Study of Undulator Tolerances for the European XFEL, TESLA-FEL Report 2007-07, DESY, Hamburg.
[7] S. Karabekyan, Local Control System of an Undulator Cell for the European XFEL, Internal EXFEL report, WP71/2010/11.
[8] W. Chen, et al., these proceedings.
[9] J. Pflueger, H.H. Lu, T. Teichmann, Nucl. Instr. and Meth. A429 (1999) 386-391.