

Automation in Commissioning Process of Undulators

ICALEPCS'15, Melbourne,19.10.2015 Suren Karabekyan The European X-Ray Free Electron Laser

XFEL Objectives

European XFEL Project

- 91 undulators are needed
- Commissioning need to be finished in 2 years, 2013 -2015
- 3 magnetic measurement labs are available
- Therefore 3 weeks were foreseen for commissioning of one undulator





XFEL Objectives



neasurement

magnetic

control

system

commissioning

- Alignment of the undulator relative to the magnetic measurement bench
- Magnetic measurements and field fine tuning
- Final measurements and documentation of magnetic properties of undulator
- Installation and adjustment of the linear encoders to achieve an accuracy of ±1µm
- Adjustment of the tilt angles of the undulator girders to better than ±150µrad
- Evaluation and implementation of the correction coefficients for rotary encoders of undulator-motors
 - Calibration of the temperature sensors











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Adjustment of the linear encoders



The installation of a profiled linear guideway has to be validated in order to ensure the requirements of the gap measurement accuracy





XFEL Adjustment of the linear encoders

The program sequentially changes the gap and reads the value of linear encoders and reference gauges

V092-T001	32406757M	324067	755N 36524228D			Right Gauge SN
1002 1001	of the second	1021007	001	00021220		0002 12010
Tolerances						
Hysteresis(mm) ±	0.002		Deviation	n(mm) ±	0.01	
Measurement Valu	es					
	100		0.ctualCa	p(mm)	00.0	0008
SetGap(mm)	100		Accoalda	p(mm)	33,33390	
Left Encoder(mm)	100.05851		Right Encoder(mm)		99.98089	
Left Gauge(mm)	100.05862		Right Gauge(mm)		99.98047	
Left Deviation(mm)	Deviation(mm) 0.00011		Right Diviation(mm)		-0.00042	
Left State			Right	State		
Setting Parameter	s					
1. Run-TimeSys	stem (PORT 801)		🔿 2. Ru	in-TimeSyste	em (PO	RT 811)
ND 287 IP Address 169.254.1.2						
Save File C:\X092-I001_2012.04.20_15h54'09".txt						
Start	Stop	G	iraph			Final state
	sion, 21. Bouision	0. Build:	26 The II	D is: 10.0.1.	92.1.1	
ormation: PLC Ver	SIGH, ST REVISION.	o balla.				





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Measurement data for Unulator SN X092-I001





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XFEL Adjustment of the tilt angle of the girders



- Due to magnetic force between upper and lower magnet structures the undulator frame bends and the girder tilt angle changes as a function of the undulator gap typically by ±250µrad
- The magnet girders of an undulator have a rotational degree of freedom
- To minimize the influence on the magnetic field the girder tilt should be adjusted symmetrically around the vertical position



XFEL Adjustment of the tilt angle of the girders



WYLER's BlueLEVEL high precision electronic inclination measuring instruments are used to measure the angles on four machined reference surfaces of the girders

 The program runs on a separate PC







0.099000

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0.112000

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-0.114000

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File Edit Format View Help

2013/01/28 22:51:55

200.0

150.0

100.0

50.0

40.0

35.0

30.0

25.0

22.0

SetGaP

XFEL Adjustment of the tilt angle of the girders

The program sequentially changes the undulator gap value and reads the tilt angle of undulator girder



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Evaluation of the feedforward correction coefficients



- Strong magnetic forces cause an elastic deformation of the undulator support frame at small gaps
- Thus cause deviations between the linear and the rotary encoder readings
- The rotary encoder reading needs to be corrected for deformation effects
- Since deformation is elastic, a feedforward correction can be applied



XFEL Evaluation of the feedforward correction coefficients

- The Gauss–Newton least-squares algorithm was used to fit the nonlinear function f(c, x) with parameters
 - $c = (c_1, c_2, ..., c_n)$ to the measured data $(x_i, y_i)(i = 1, 2, ..., m)$
- This algorithm minimizes the sum of squares $R = \sum_{i=0}^{n} [f(c, x_i) - y_i]^2$ of residual errors $r_i = f(c, x_i) - y_i$
- Minimum is achieved when the partial derivatives with respect to the parameters are zero $\frac{\partial R}{\partial \delta c_j} = 2 \sum_i r_i \frac{\partial r_i}{\partial c_j} = 0 \ (j = 1, ..., n)$
- A fitting function of the form $f(c, x) = c_1 + c_2 * e^{-\frac{(x-x_0)}{c_3}}$ was chosen and is used in the program



XFEL Evaluation of the feedforward correction coefficients

The program sequentially changes the gap and calculates the deviation between linear and rotary encoders

Undulator SN	Left End	Left Encoder SN			
X044-K004	388352	38835248T			
tting Parameter					
XO	5				
easurement Values					
SetGap(mm)	10	ActualGap(mm)	10.00006		
Left Encoder(mm)	9.14463	Right Encoder(mm)	9.29444		
Left Deviation(mm)	0.42772	Right Diviation(mm)	0.35281		
etting Parameters —			-		
1. Run-TimeSyste	em (PORT 801)	C 2. Run-TimeSyst	em (PORT 811)		
Configuration File	C:\Public\CorrCoeffGen\v1.1\CorrectionCurves3times:				
Save File	C:\X044-K004_2015.10.09_20h06'33".txt				
Start	Stop	Fit			





Measurement data for Unulator SN X044-K004





SetGa	P ActGap	LeftLC	RightLC	LeftDeviation	n RightDevia
200.0	200.00006	199.90714	200.00731	0.04646	-0.00363
180.0	180.00006	179.90684	180.00908	0.04661	-0.00451
160.0	160.00006	159.90996	160.01129	0.04505	-0.00561
140.0	140,00006	139,91182	140,01247	0.04412	-0.00620
120.0	120.00006	00.01105	120.01420	0.04321	-0.00707
90.0	90,00006	89 91281	90.01129	0.04363	0.00592
80.0	80 00006	79 91335	80.01219	0.04336	0.00606
70.0	70.00006	69.91461	70.01090	0.04273	-0.00542
60.0	60.00006	59.91463	60.01100	0.04272	-0.00547
55.0	55.00006	54.91490	55.00692	0.04258	-0.00343



XFEL Calibration of temperature sensors for undulator cell

Objective

- Temperature may vary along the tunnel
- NdFeB permanent magnet used for the XFEL undulators has reversible temperature coefficient $\eta \approx -1.1 \times 10^{-3} / {}^{\circ}C$

Solution

- Gap correction method will be used to compensate for magnetic field changes
- Each undulator is equipped with temperature sensors



$$\Delta g = \frac{\lambda_U \eta}{b + 2cg / \lambda_U} \Delta T$$

• $\Delta T = T_{Nom} - T_{Act}$, T_{Nom} is the nominal temperature T_{Act} is the actual temperature λ_U is the undulator period length g is the undulator gap b and c are empirical constants



Automation in Commissioning Process of Undulators

- All temperature sensors together with a certified reference temperature sensor are thermally connected to an aluminum block and inserted into a thermostabilized water bath in a thermostat
- Its temperature could be controlled to proceed with calibration measurements that will allow finding of the offset and slope at 0°C for calibrating sensors





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Automation in Commissioning Process of Undulators



XFEL Calibration of temperature sensors for undulator cell

Each sensor is equipped with a memory block, which allows saving the calibration coefficients

Undulator No.	X021-N019			Undulator No	X021-N019		
AMS	5.17.239.70.1.1			AMS	5.17.239.70.1.1		
Save Path	C:\X021-N019_2014.03.	.06_23h25'34.txt		Save Path	C:\X021-N019_2014.0	03.06_23h25'34.txt	—]
Connections ALMEMO Serial Port	HAAKE Serial Port	HAAKE Temperature Set (°C)	Actual (°C)	Connections ALMEMO Serial P	ort HAAKE Serial Port	HAAKE Tempe Set (°C)	Actual (°C)
СОМЗ 💌	COM4 💽	18.0	17.99	сомз 🖵	COM4 -	16.0	26
Temp Set Parameters Start (°C) 16 • ALMEMO 18.161	(* 1. Calibration End (*C) Step(* 26 1 M1 22.488		Monitor(min)	Temp Set Paramete Start (°C) 16 M0 18.048	C 1. Calibration ers End (°C) Step 26 ✓ 1 M1 22.954	(°C) (°C) Waiting Calibrai 120 M2 22.866	D Time tion(s) Monitor(min) 1 1 M3 22.658
Deviation	0	0		Deviation -0.002	-4.909	-4.82	-4.614
Undulator Left	Middle 18.358	Right Vac Ch 17.984 18.08	amber 5	Undulator Left	Middle 18.045	Right 18.046	Vac Chamber
	Start	Stop Calibrate	Cancel		Start	Stop Ca	alibrate Cancel

l	File Edit Format	View Help					
	X021-N019 2014/03/06 23: ALMEMO Device MO Sensor Seri M1 Sensor Seri M2 Sensor Seri Diff=Callibrat ActualTem	50:56 Serial No. al No. : al No. : al No. : al No. : ingSensor\ LSensor	: T0912 DKD-K DKD-K DKD-K MKD-K DKD-K MSensor	0225 -06701 -06702 -06703 -06704 enceSensorV RSensor	alue VCSensor	LDiff	MDii
	16.160 17.159 18.161 19.146 20.140 21.137 22.132 23.123 24.127 25.116 26.117 Left sensor Widdle sensor Vacuum Chamber X021-N019	16.070 17.068 18.069 19.053 20.047 21.040 22.036 23.024 24.027 25.017 26.016 linear fit linear fit sensor li	16.350 17.351 18.357 19.344 20.340 21.338 22.336 23.329 24.335 25.329 26.330 tting: tting: near fitti	15.977 16.978 17.983 18.969 19.963 20.959 21.957 22.949 23.954 24.944 25.946 y=-0.0 y=0.0 y=0.0	16.085 17.084 18.085 19.070 20.063 21.059 22.053 23.043 24.046 25.038 26.035 0012 x+(-0.16 0006 x+(-0.06) 0006 x+	-0.090 -0.091 -0.092 -0.093 -0.093 -0.097 -0.097 -0.098 -0.100 -0.101 071) 3) 99)	0.1 0.1 0.1 0.2 0.2 0.2 0.2 0.2 0.2 0.2
	2014/03/06 23: ALMEMO Device MO Sensor Seri M1 Sensor Seri M2 Sensor Seri M3 Sensor Seri Diff=Callibrat Time	55:53 Serial No. al No. : al No. : al No. : al No. : ingSensor\ MO	: T0912 DKD-K DKD-K DKD-K DKD-K Alue-Refer Left D	0225 -06701 -06702 -06703 -06704 enceSensorv eviation	alue M1	Middle	Dev.
	t C C C C Left Down C	y=-0.0012 x+(-0.071)	2nd Of	fset	5.167 16.158 5.156 5.157 5.157 5.157 5.160 16.157	-6. -6. -6. -6. -6.
	C Middle Up Right Down	y=0.0023 x+(i	0.153) -0.199)	0		5.157 5.184	-6. -6.
	Vaccum Chamber	y=-0.0006 x+	(-0.064)	0			
				Apply	Cancel	1	

After evaluation of the offset and slope the program could write these values directly into the memory block of calibrated sensor

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XFEL Conclusion



- A modular concept allowed to build flexible frame for development of several automation programs
- The use of automation programs allowed to reduce the time spent for the commissioning of the control system by an order of magnitude
- The commissioning of all undulators have been successfully finalized in 2015

Thank you for your attention!