Undulator Manufacturing for the European XFEL

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On behalf of Undulator Systems Group (WP71)
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Overview

- European XFEL facility overview
  - Undulator system
- Undulator Segments
  - Serial Production of Undulator Segments:
    - External Production in Industry
    - XFEL.EU – WP71 Part
  - Representative Results
- Intersection Components
- Controls
- Undulator Systems
  - Installation
  - Commissioning
  - Maintenance

Facility overview

Schenefeld

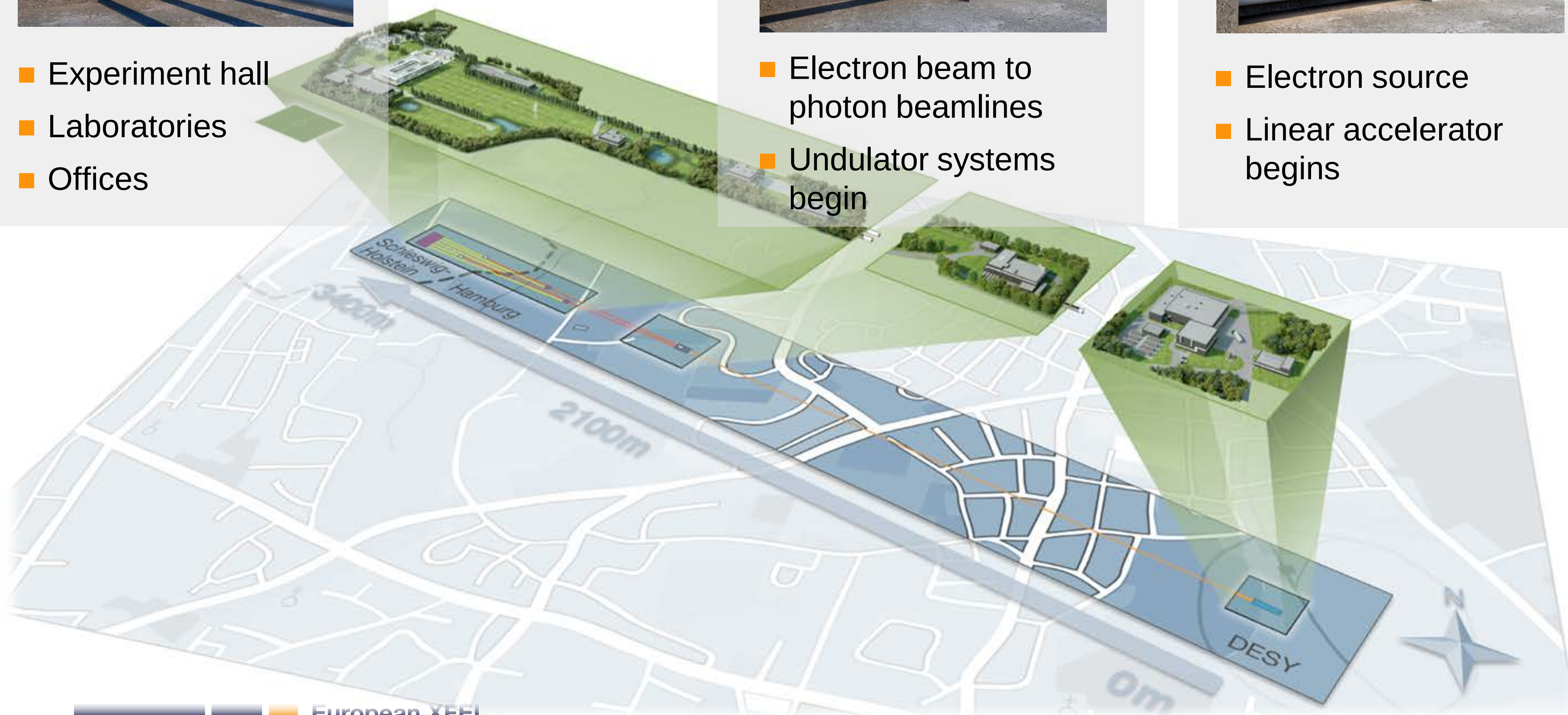
- Experiment hall
- Laboratories
- Offices

Osdorfer Born

- Electron beam to photon beamlines
- Undulator systems begin

DESY-

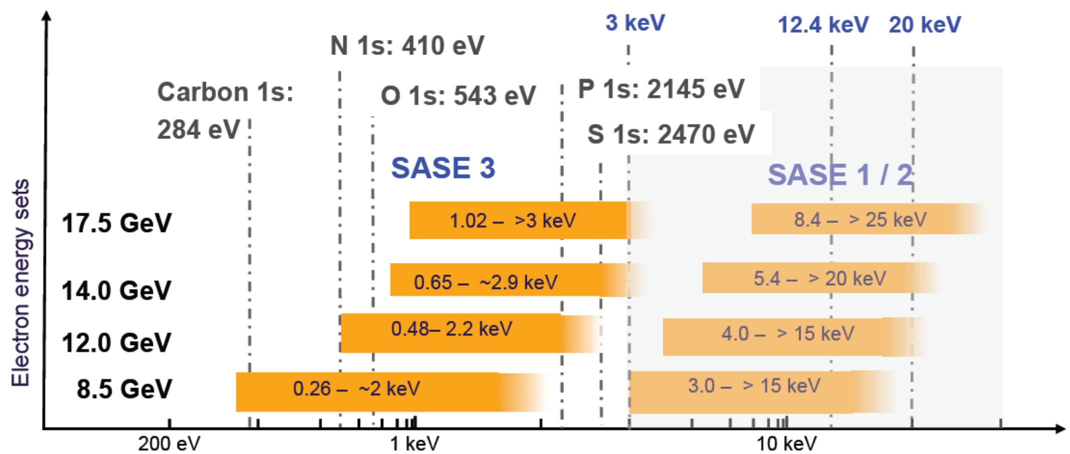
- Electron source
- Linear accelerator begins

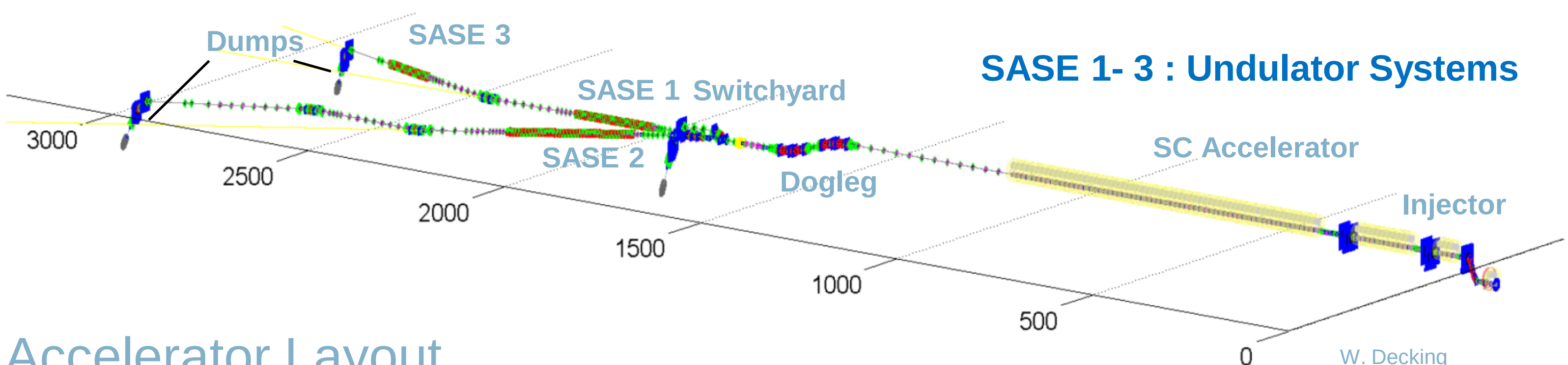


Undulator Systems

	SASE1/2	SASE3
λ_u [mm]	40	68
Operational Gap Range [mm]	10-20	10-25
K-Range	3.9–1.65	9.3-4
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
@ 12.0 GeV	0.310-0.0828	2.44-0.621
@ 8.5 GeV	0.625-0.171	5.17-1.15
Number of Segments	35	21
System Length [m]	213.5	128.1

Photon Energy Range





SASE 1- 3 : Undulator Systems

Accelerator Layout

High repetition rate: < 27000 pulses/ sec

Production Cycle

External Production in Industry and XFEL.EU – WP71 Part

- Synergistic R&D together with DESY until 2008
- Industry Involvement
  - Mechanical Support System : 2 Suppliers
  - Magnetic Structure
  - Local Motion Control
- Work done @ XFEL.EU
  - Mechanics + Magnetics Integration @ XFEL.EU
  - Commissioning @XFEL.EU
  - Magnetic Measurement & Tuning
  - Document Management System

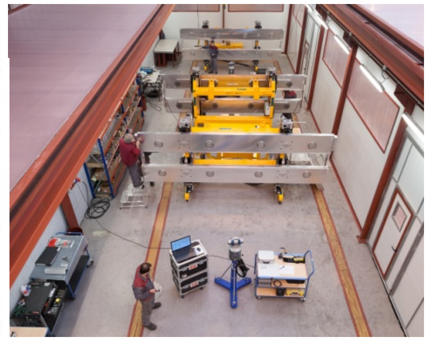
Serial Production of Undulator Segments:
External Production in Industry

Mechanical Support Systems

KINKELE

Dec 2012

NORTEMECANICA, S.A



July 2012

Dec 2012

Magnetic Structuress

VAC VACUUMSCHMELZE

Nov 2012

Local Control Systems

BECKHOFF New Automation Technology

Nov 2012

Production at European XFEL in Hall 5

New Undulator Segments

3 climatized Magnetic Labs

Assembly Area for Magnetic Structures

Segments waiting for Magnetic Measurements

Measured and tuned Segments

Incoming Magnetic Structures from VAC

Steps @ XFEL.EU:

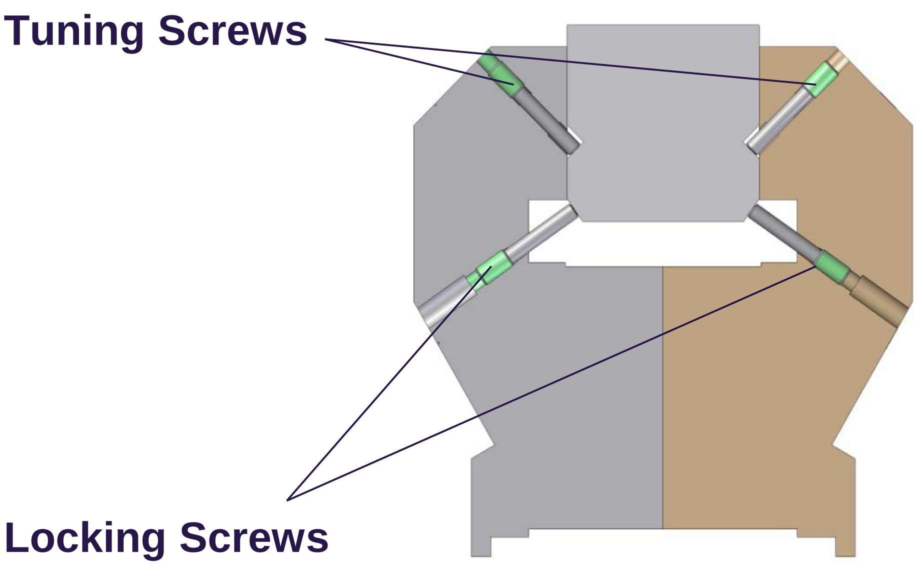
- **Mounting of magnetic structures**
- **Local Control System Commissioning**
- **Magnetic Measurements & Tuning**
- **Documentation, Preparation for Installation**

Schedule:

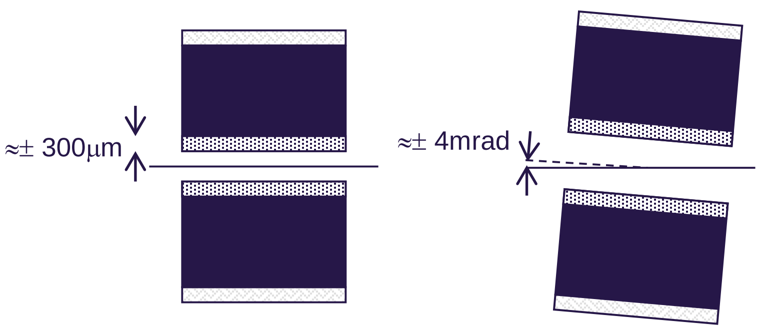
- **Total Time ≈ 2 Years (starting Oct/12)**
- **Scheduled End: Oct / End 2014**
- **→ 3 Magnetic Labs needed running in parallel**
- **3 Weeks/Undulator**

Hall 5 was rapidly filled up. Assembled and tuned undulators were stored in a hall, outside of DESY premises .

Magnetic Measurements:
Field Error Correction by Pole Height and Tilt Adjustment



- **Adjustment Range:**
- **Pole Height : ± 0.3mm**
- **Pole Tilt : ± 4mrad**

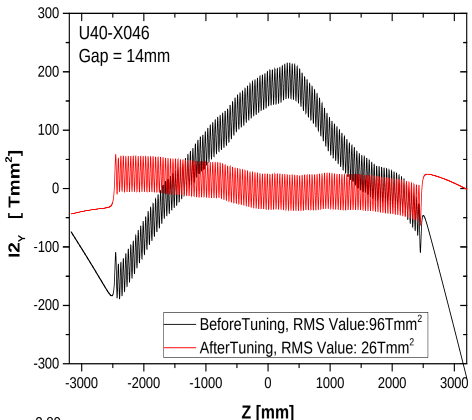


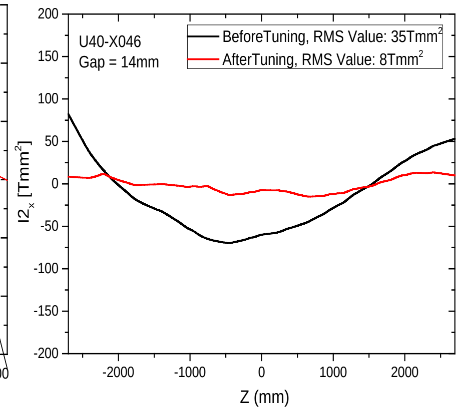
- **Bipolar Field Corrections**
- **No Shims are used**
- **All errors are tuned by moving Poles**

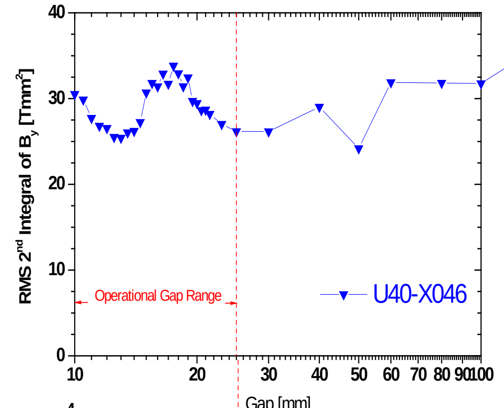
Basics: J. Pflüger, H. Lu, T. Teichmann NIM A429 (1999), 368

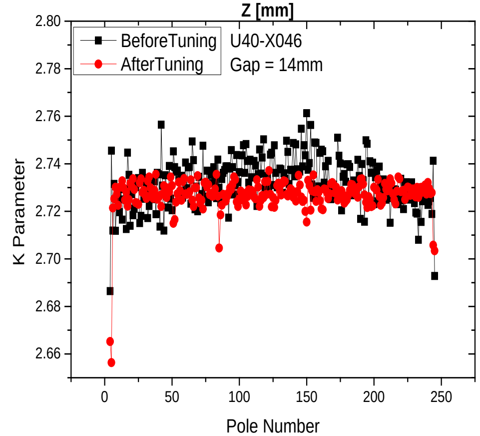
Undulators: Representative Magnetic Results: U40-X046

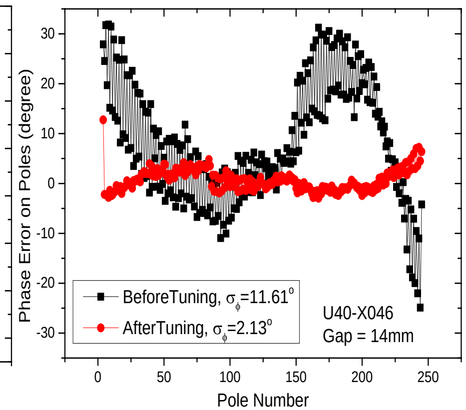
XFEL Specs	U40	U68
Operational Gap Range [mm]	10-20	10-25
B_0 @ 10mm Gap [T]	1.14	1.66
K @ 10mm Gap	3.9	9.0
RMS $I2_Y$ [Tmm²]	< 100	< 210
RMS $I2_Z$ [Tmm²]	< 100	< 100
Phase Jitter [°]	≤ 8	≤ 8

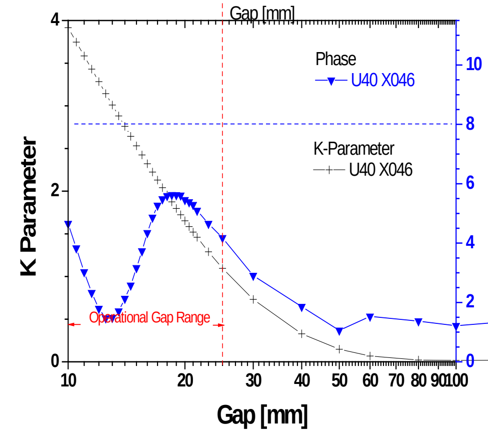












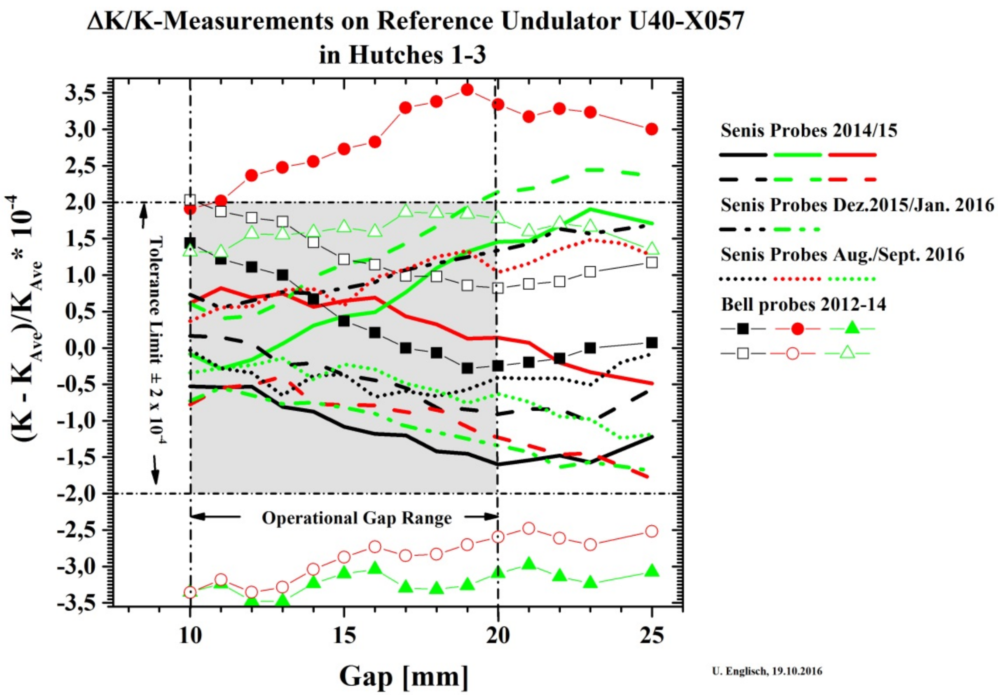
Re-Measurement Campaign

Reasons:

1. 60% of the Undulator Segments were stored outside up to 2 ½ years with no temperature control (8-30° C) Check prior to installation requested!
2. Improve accuracy of Hall Probe measurements and transferability between the labs to ΔK/K =2 x 10^{-4} using new high stability, low drift, low noise probes (SENIS H3A-0YJ02F-B02T0K5K)
3. Apply exactly the same specs and procedures to all segments.
4. Precision Air Coil settings for Entrance/Exit Kicks using the Long Moving Wire Method rather than Hall Probes.

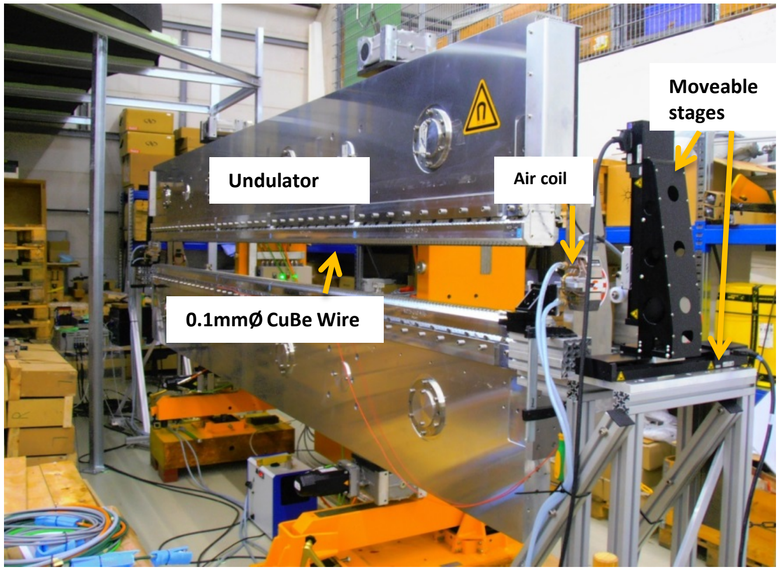
Results:

- Only minor changes observed (entrance/exit kicks)
- Phase Jitter, straightness unchanged
- Probe data are much more stable

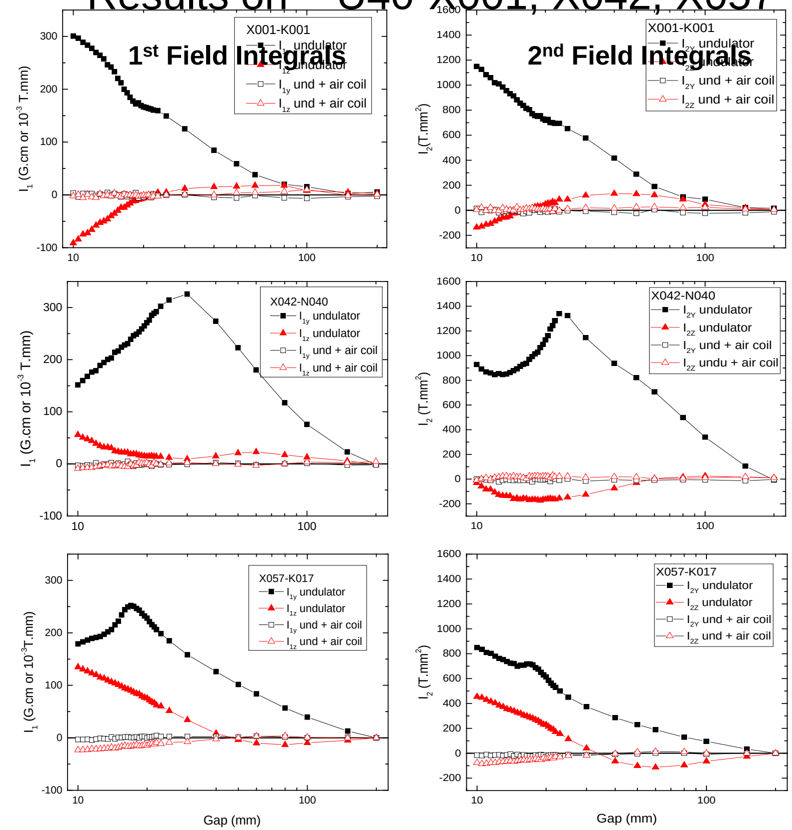


Message: Accuracy Limit, ΔK/K ≤ ±2.0x10^{-4} during the whole re-measurement campaign Fall 2014 – September 2016

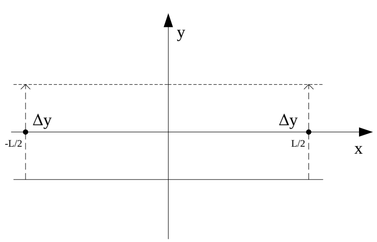
Measurement of Entrance and Exit Kick using the Moving Wire



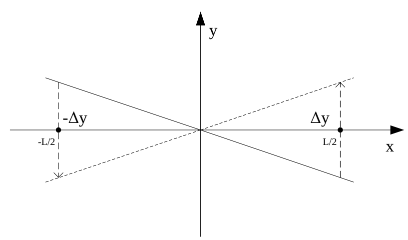
Results on U40-X001, X042, X057



Paralell "P"



Anti-Paralell "A"



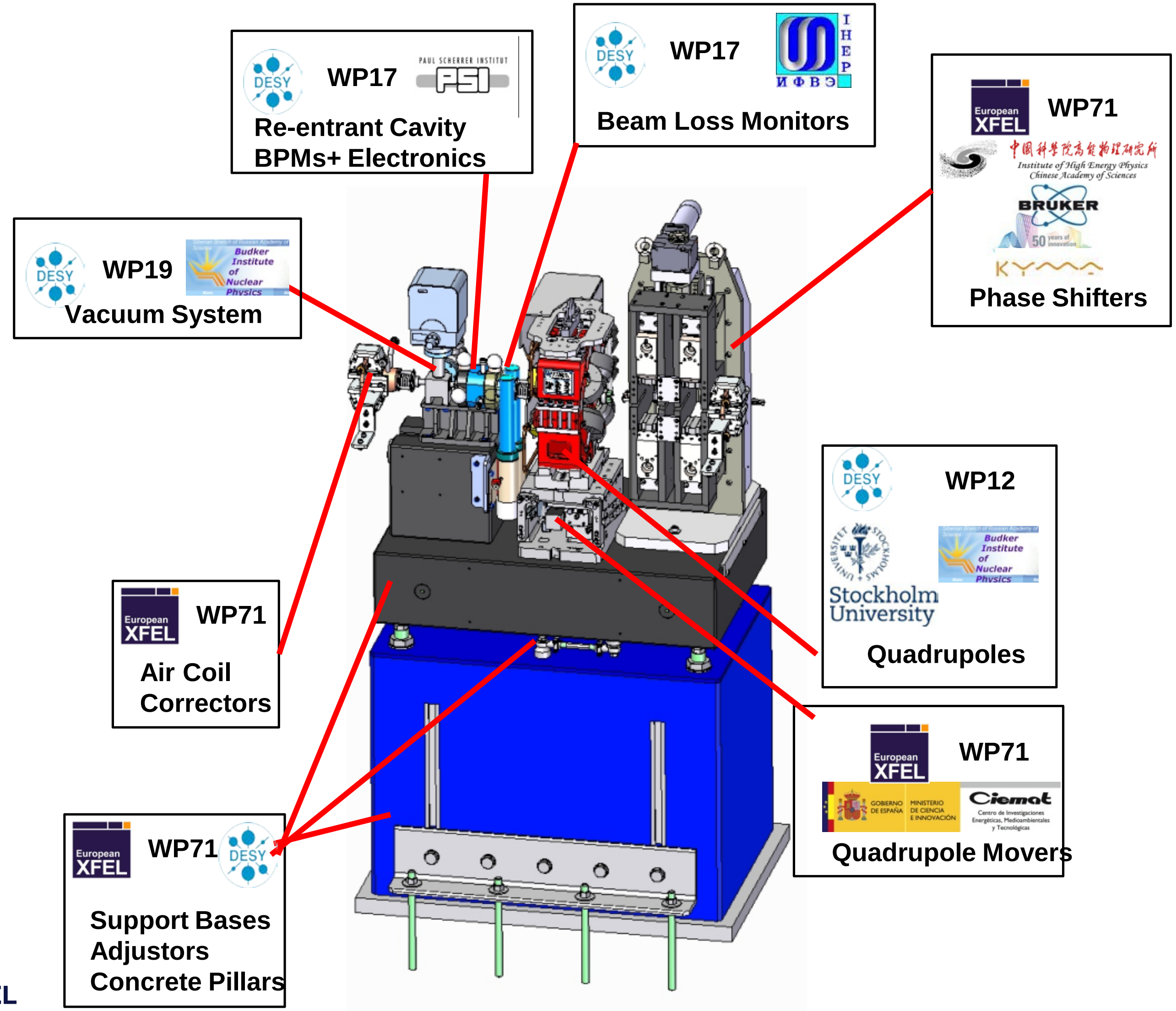
$$I1_B = \frac{\Delta\phi_P}{N\,\Delta y, z}; \qquad I2_B = \frac{L/2}{N\,\Delta y, z}\{\Delta\phi_P - \Delta\phi_{AP}\}$$

D. Zangrando, R.P. Walker, Nucl. Instr. And Meth, A376 (1996), 275

Accuracy: $\Delta I1 \le \pm 5$Gcm; $\Delta I2 \le \pm 2000$ G.cm ^{2}

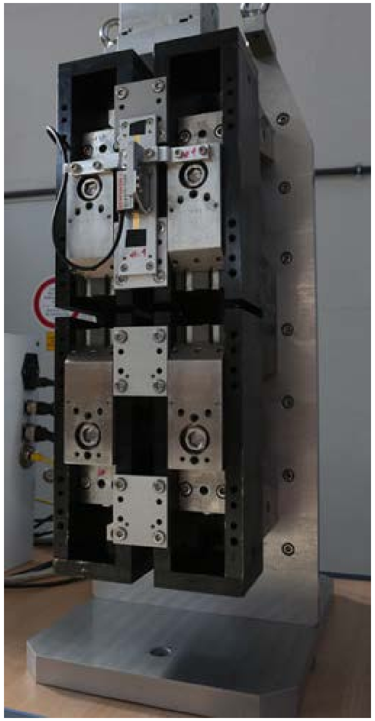
Intersection

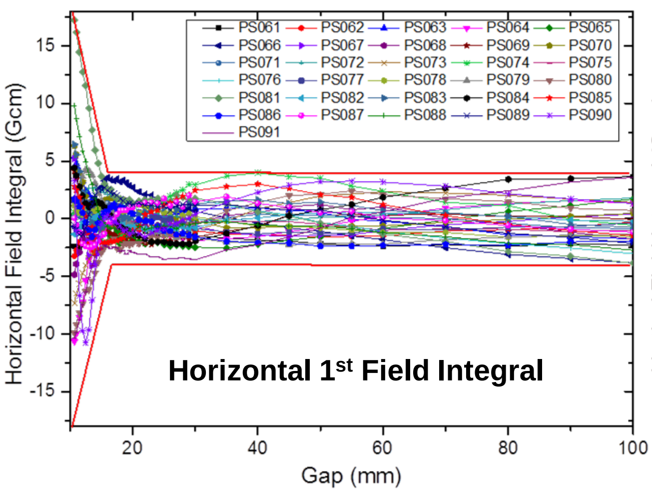
- Undulator System Group (WP71) is responsible for the following components: Quadrupole Mover, Phase Shifter, Air coils, Support basies, Intersection Control Racks,
- 9 companies were producing the intersection components for WP71

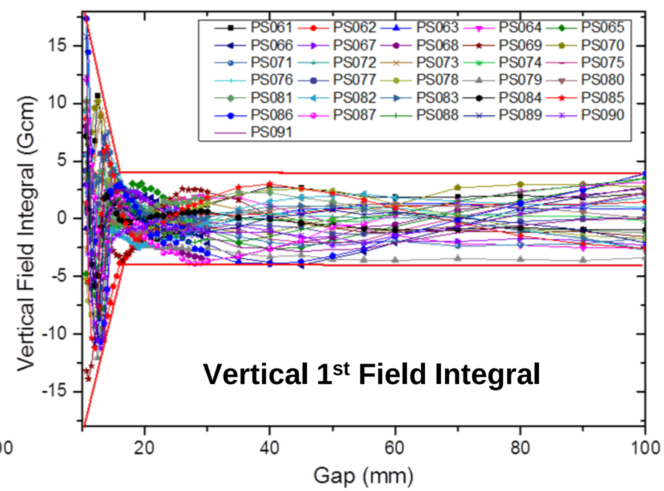


Phase Shifters with very low 1st Field Intergral errors: Representative Results

- Period length: 55mm
- Gap range: 10.5 to ≈>100mm
- Max. Phase Integral @ gap 10.5mm : ≥23400 T^2mm^3
- **1st Hor/Ver Field Integral Tolerance: ±0.004 Tmm**
- **Dynamic Operation without retuning!**
- 2nd Hor/Ver Field Integral Tolerance: ±67 Tmm^2
- Min. Gap precision for 5° SASE1/2 ±15µm







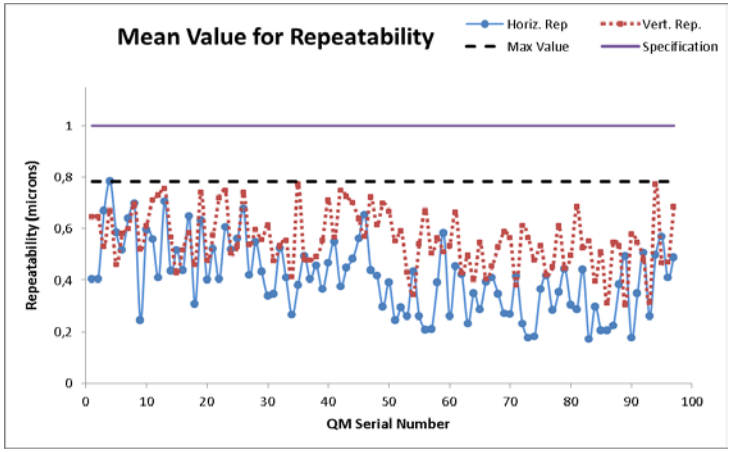
Y. Li, J. Pflueger, Phys. Rev. STAB 18, 030703 (2015)

$$\Delta\varphi = \frac{2\pi}{\lambda_0\left(1+0.5K^2\right)}\left(\frac{e}{mc}\right)^2 PI = \frac{2\pi}{\lambda_R 2\gamma^2}\left(\frac{e}{mc}\right)^2 PI$$

- 1st Field Integrals: Important for independent operation, no corrections required (**31 Phase Shifters , Huihua Lu, Lingling Gong, Yajun Sun, IHEP**)

Intersection

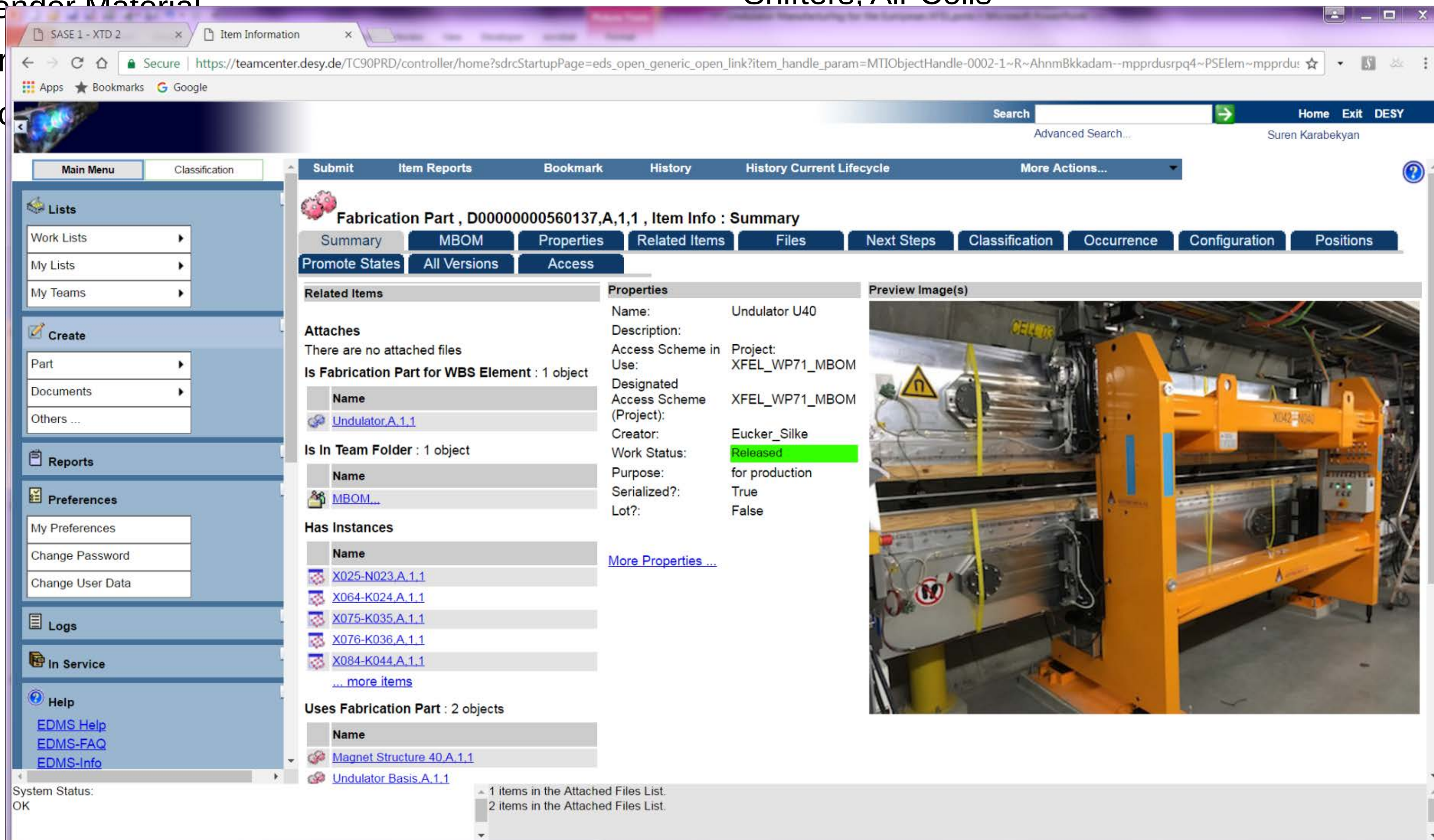
- Factory acceptance tests (FAT) have been requested: Documentation stored in the EDMS
- All necessary hardware for the FAT have been provided by European XFEL
- After delivery of all components to European XFEL, site acceptance tests were arranged.
- If any of the components didn’t match the specifications, this component was sent back to the manufacturer
- Our experience has demonstrated that after the SAT only 1% of the delivered QMs and PSs needed to be returned.
- Approximately the same failure rate has been observed for ICRs
- No returns for Air coils and Support bases



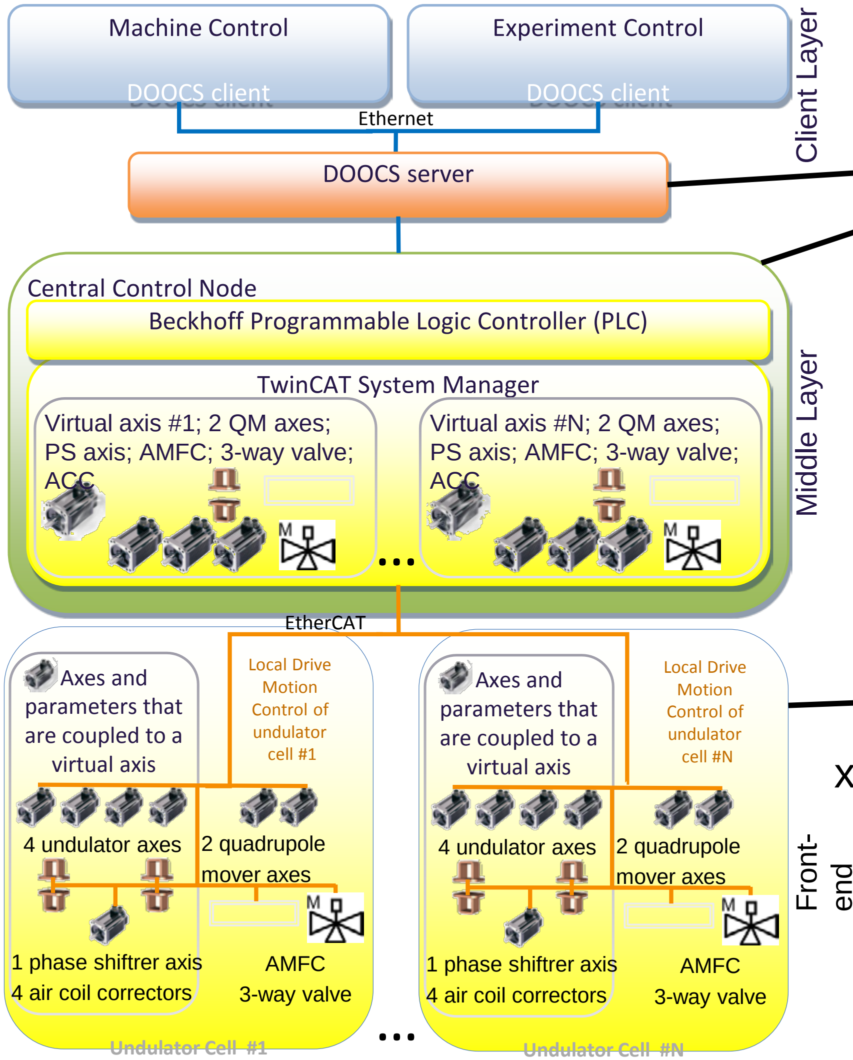
Documentation Database in EDMS

- Drawings
- Tender Material
- Pr
- Ac

- Magnetic data of all Undulator Segments, Phase Shifters, Air Coils



Undulator Controls System



x 1

CCN in Balcony Room in XHEXP

x 35

LCN in SASE1

- The undulator control system is based on industrial components produced by Beckhoff company and a PLC implemented in the TwinCAT system.

Undulator Local Controls System: Commissioning in the Labs

- Magnetic measurements
  - ► 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

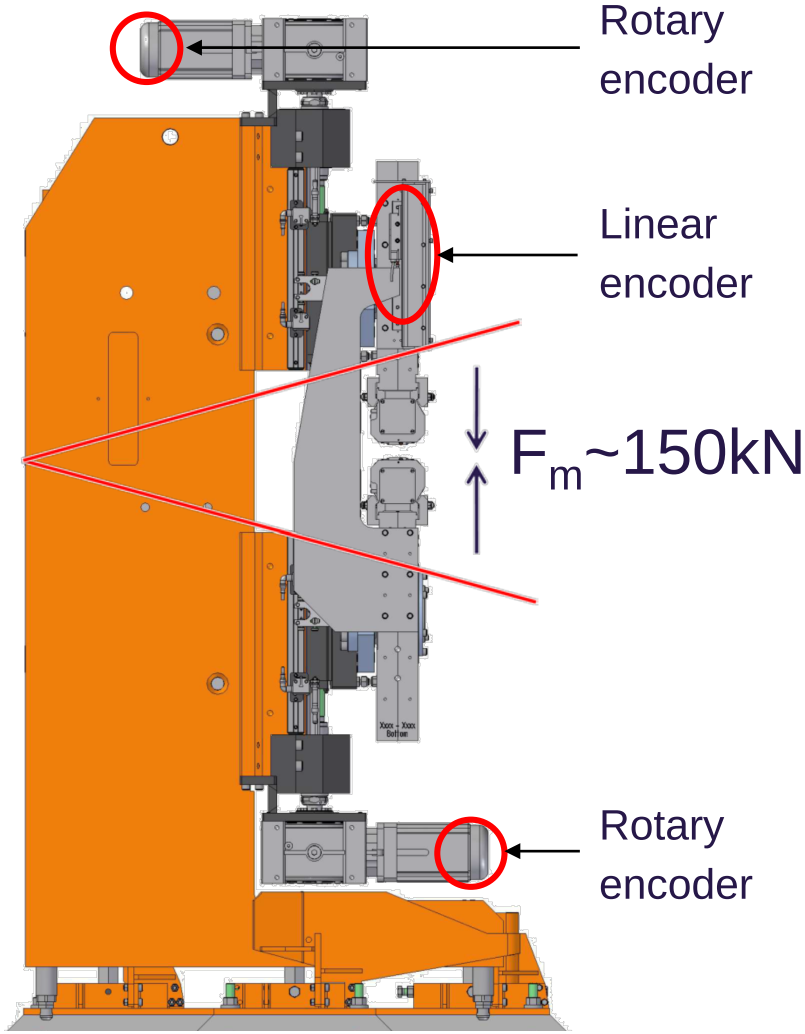
Semi-automated
Duration ~ 2.5 weeks

- Control system commissioning
  - ► Installation and adjustment of the linear encoders to reach an accuracy of ±1μm.
  - ► Adjustment of the tilt angles of the undulator girders to better than ±150μrad
  - ► Evaluation of the feedforward correction coefficients for the rotary encoders
  - ► Calibration of the temperature sensors

Were not automated
Duration ~ 2.5 weeks

Without automation of the control system commissioning 3 Weeks/Undulator production speed will be inposible

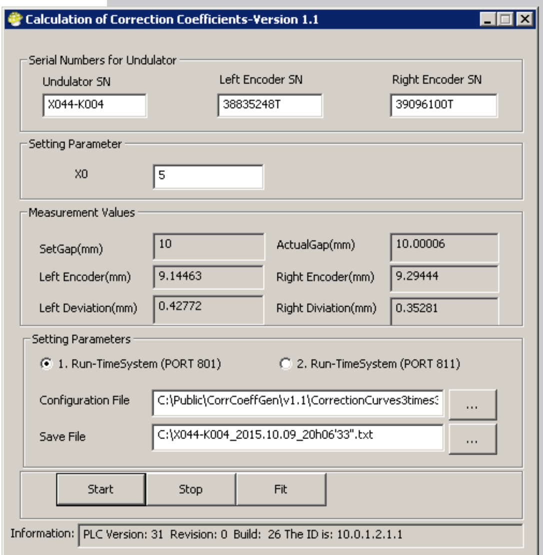
Evaluation of the feedforward correction coefficients

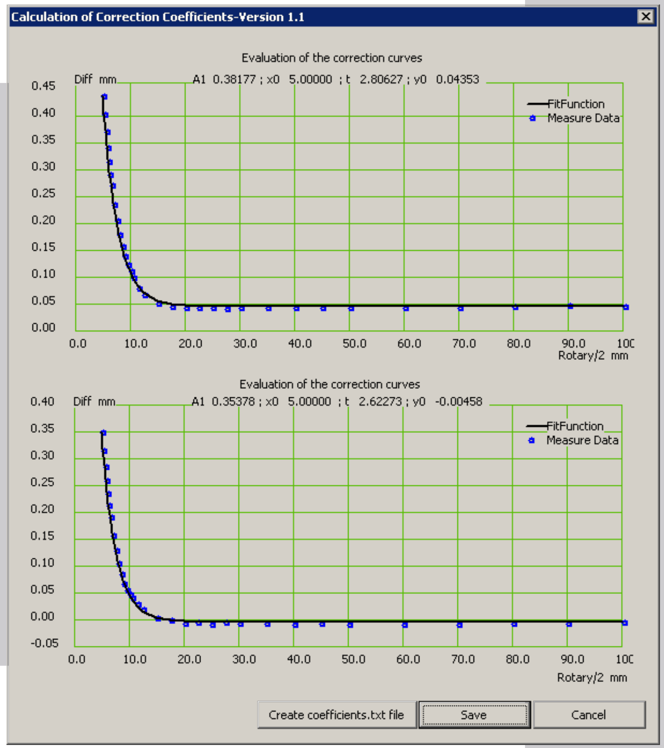


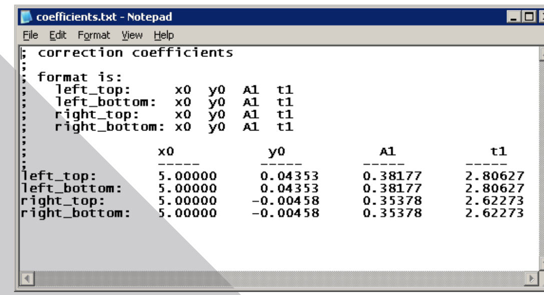
- Strong magnetic forces cause an elastic deformation of the undulator support frame at small gaps
- Thus cause deviations between the linear and the rotary encoder readings
- The rotary encoder reading needs to be corrected for deformation effects
- Since deformation is elastic,
  a feedforward correction can be applied
- The Gauss–Newton least-squares algorithm was used to fit the nonlinear function $f(\boldsymbol{c},x)$ with parameters $\boldsymbol{c} = (c_1, c_2, \dots, c_n)$ to the measured data $(x_i, y_i)(i = 1, 2, \dots, m)$.
- A fitting function $f(\boldsymbol{c}, \mathrm{x}) = c_1 + c_2 * e^{-\frac{(x-x_0)}{c_3}}$ was selected and is used in the program

Evaluation of the feedforward correction coefficients

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

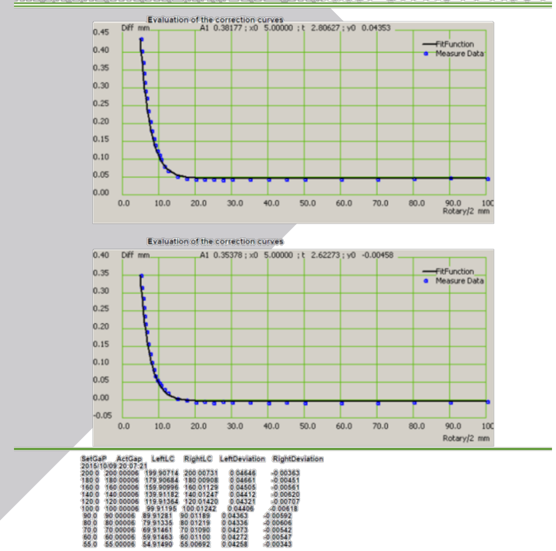





coefficients.txt - Notepad

```
; correction coefficients
;
; format is:
;    left_top:     x0  y0  A1  t1
;    left_bottom:  x0  y0  A1  t1
;    right_top:    x0  y0  A1  t1
;    right_bottom: x0  y0  A1  t1
;
;                x0         y0         A1         t1
;               -----      -----      -----      -----
left_top:      5.00000    0.04353    0.38177    2.80627
left_bottom:   5.00000    0.04353    0.38177    2.80627
right_top:     5.00000   -0.00458    0.35378    2.62273
right_bottom:  5.00000   -0.00458    0.35378    2.62273
```

Measurement data for Unulator SN X044-K004



Software for commissioning of an undulator system
Image Deployment Automation Components

- A specific feature of undulator systems for free-electron lasers is the large number of repeating elements.
- The software running on each LCN must be identical, although each cell component has its individual settings
- The other aspect is the need to have possibilities to update the version of the TwinCAT software as well as specific firmware.
- These arguments lead to the decision to develop software which will automate this process

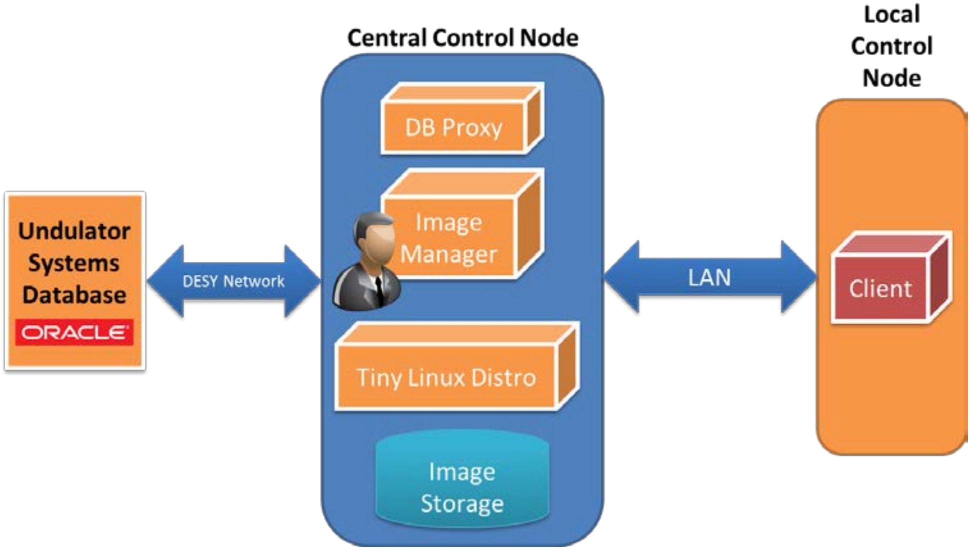


Image Deployment Automation: Components

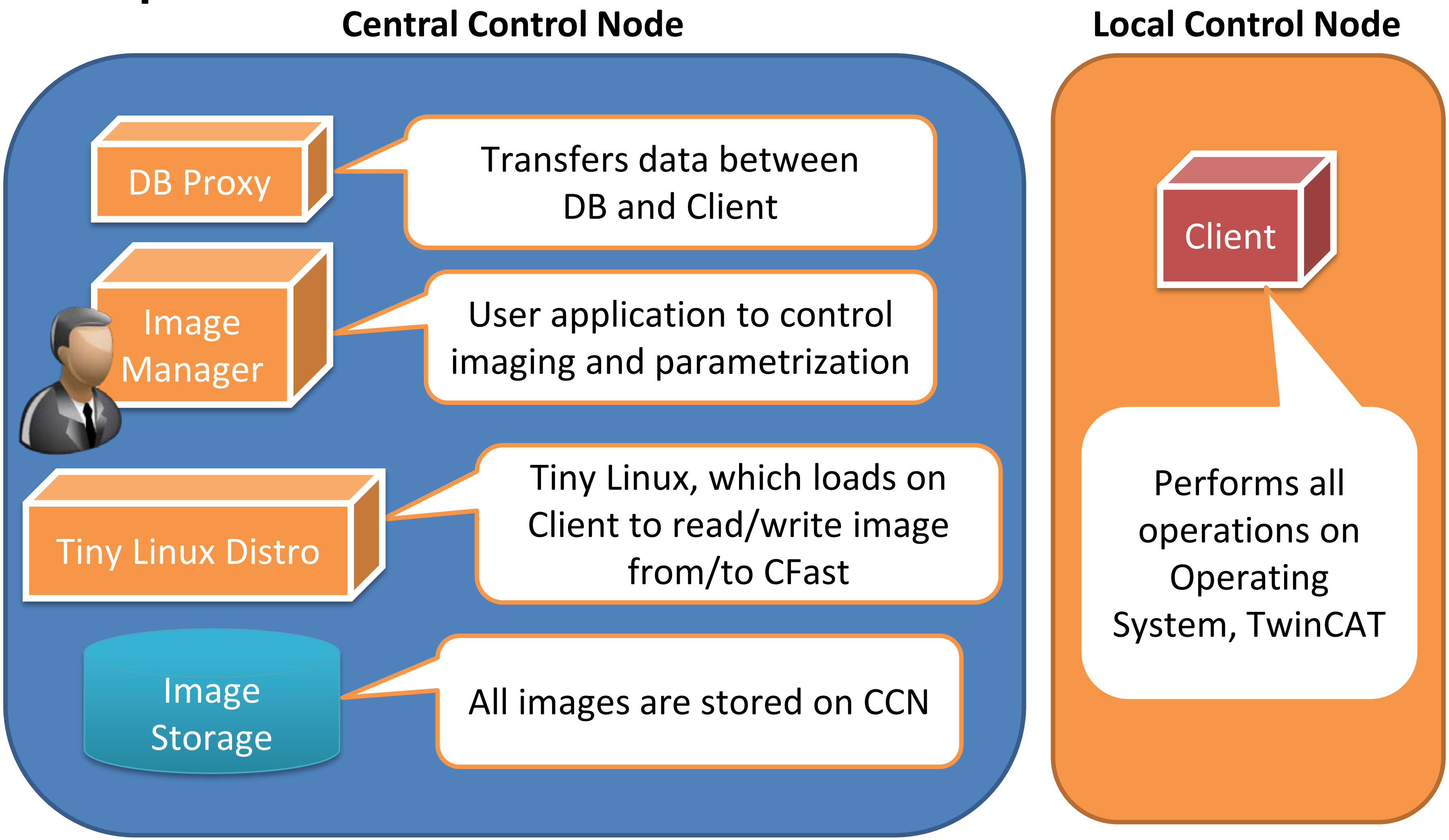


Image Deployment Automation
Upda

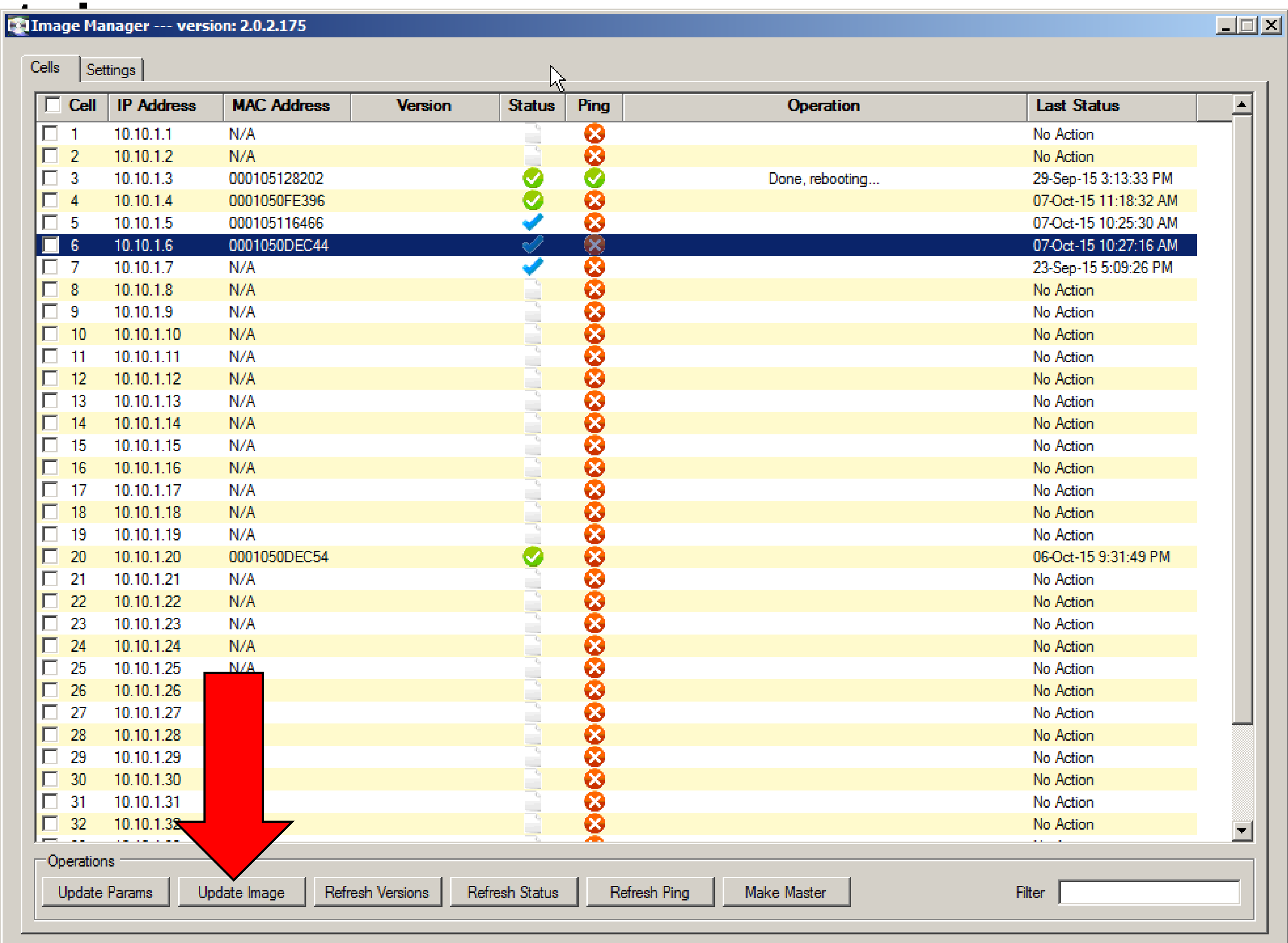


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Image Deployment Automation

Up

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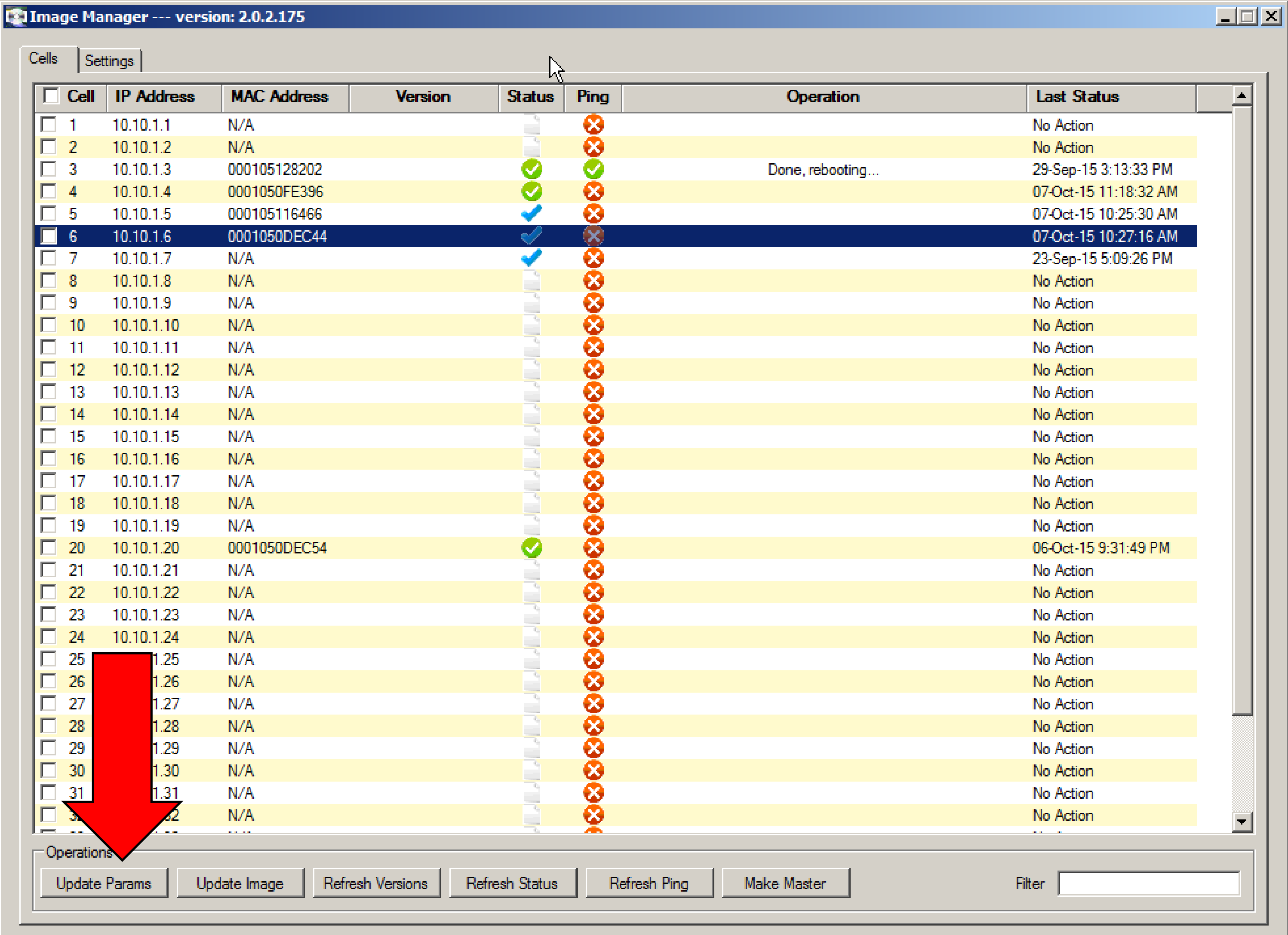

Cell	IP Address	MAC Address	Version	Status	Ping	Operation	Last Status
1	10.10.1.1	N/A					No Action
2	10.10.1.2	N/A					No Action
3	10.10.1.3	000105128202				Done, rebooting...	29-Sep-15 3:13:33 PM
4	10.10.1.4	0001050FE396					07-Oct-15 11:18:32 AM
5	10.10.1.5	000105116466					07-Oct-15 10:25:30 AM
6	10.10.1.6	0001050DEC44					07-Oct-15 10:27:16 AM
7	10.10.1.7	N/A					23-Sep-15 5:09:26 PM
8	10.10.1.8	N/A					No Action
9	10.10.1.9	N/A					No Action
10	10.10.1.10	N/A					No Action
11	10.10.1.11	N/A					No Action
12	10.10.1.12	N/A					No Action
13	10.10.1.13	N/A					No Action
14	10.10.1.14	N/A					No Action
15	10.10.1.15	N/A					No Action
16	10.10.1.16	N/A					No Action
17	10.10.1.17	N/A					No Action
18	10.10.1.18	N/A					No Action
19	10.10.1.19	N/A					No Action
20	10.10.1.20	0001050DEC54					06-Oct-15 9:31:49 PM
21	10.10.1.21	N/A					No Action
22	10.10.1.22	N/A					No Action
23	10.10.1.23	N/A					No Action
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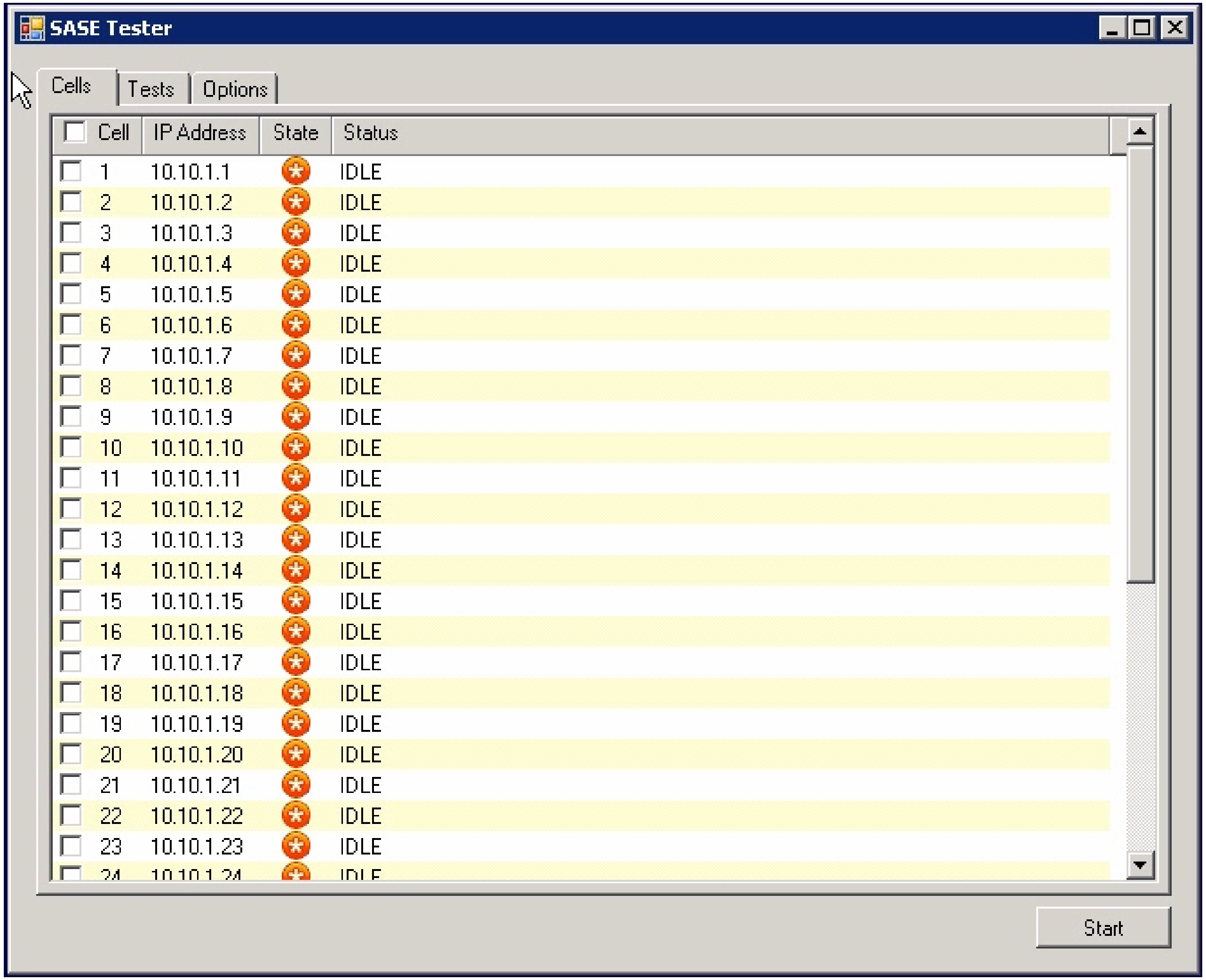
25	1.25	N/A					No Action
26	1.26	N/A					No Action
27	1.27	N/A					No Action
28	1.28	N/A					No Action
29	1.29	N/A					No Action
30	1.30	N/A					No Action
31	1.31	N/A					No Action
3	2	N/A					No Action

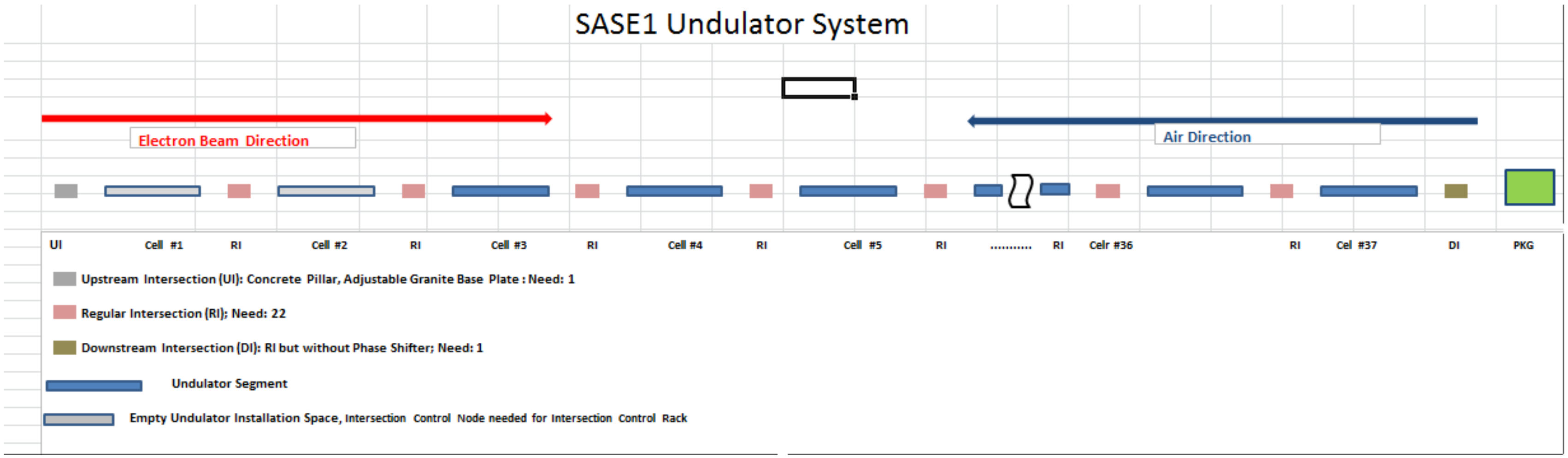
Undulator System Tester

- The next step after putting the undulator system into operation is the commissioning of all control components that belong to it
- This task could be time consuming because several hundred values per system must be examined.
- This was a motivation to create a supervisory control and data acquisition (SCADA) program.
- This program is running on the CCN and is sending commands to the LCNs.
- After the execution of the commands, the program receives a feedback value.
- If the value is inside of an expected range, then the test is accepted; otherwise the test is marked as not successful.

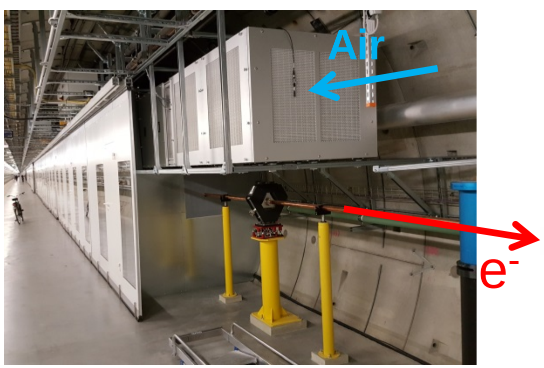
Undulator System Tester



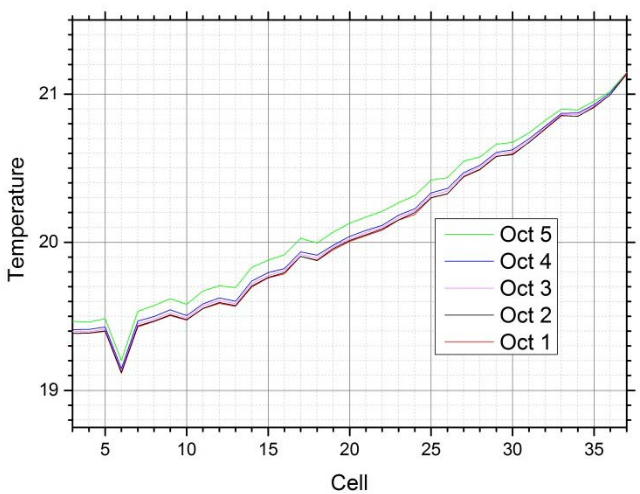
Temperature Distribution in SASE1 System measured Sep.3 – Oct. 3 (Holidays)



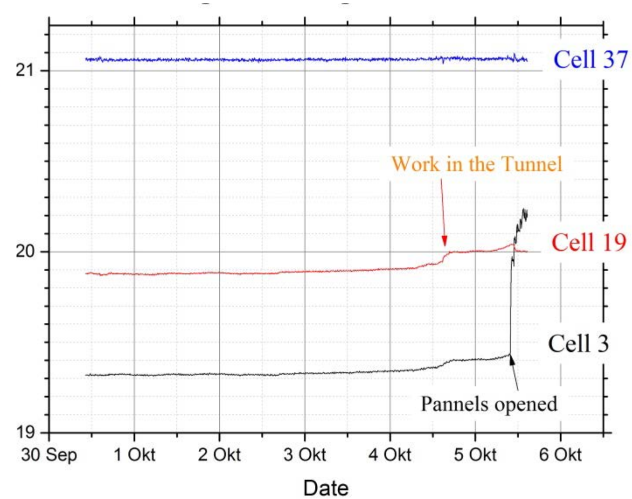
SASE1 PKG



Temperature along SASE 1

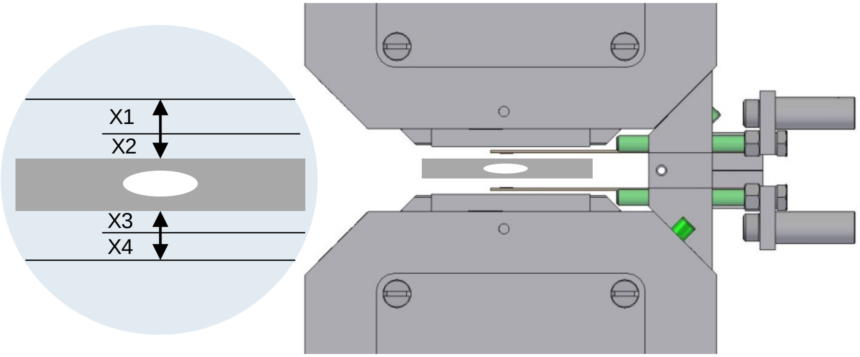


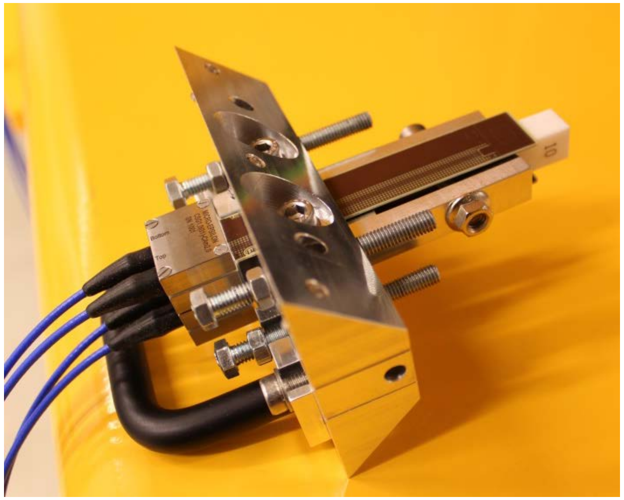
Time Dependence at Cells 3, 19,37



Hardware Management in Tunnel:
Reference Gap Measurement Device

- Gap measurement principal
  - ▶ 4 Micro-Epsilon calibrated capacitive sensors
  - ▶ @ constant gap and thickness of vacuum chamber ∑ is constant
  - ▶ Holder fixed using magnetic force
  - ▶ Sub micrometer measurements reproducibility
  - ▶ Measurements are independent from the temperature of the holder and quasi-independent from the temperature of the sensors
  - ▶ With non magnetic gauge can be used without vacuum chamber





Undulator Systems Instalation in the Tunnel

Status of SASE1 & SASE3 May 2017

Status

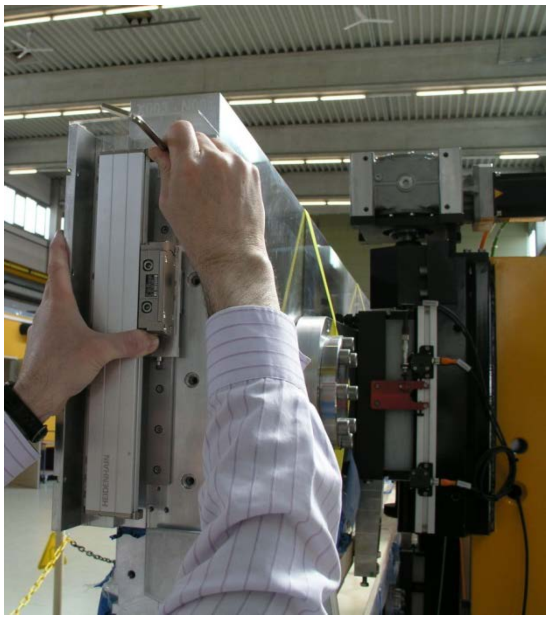
- Undulator Hardware installed: Quadrupoles, Quadrupole Movers, Magnet Power, Cooling Water, Phase Shifters,
- Undulator Control System commissioned, operational
- Undulator System aligned with SLRS
- Interlocks installed
- Air Conditioning System installed & commissioned
- **SASE1 System “Ready for Beam“ since March, 2017**
- **SASE3 System “Ready for Beam“ since April 14, 2017**

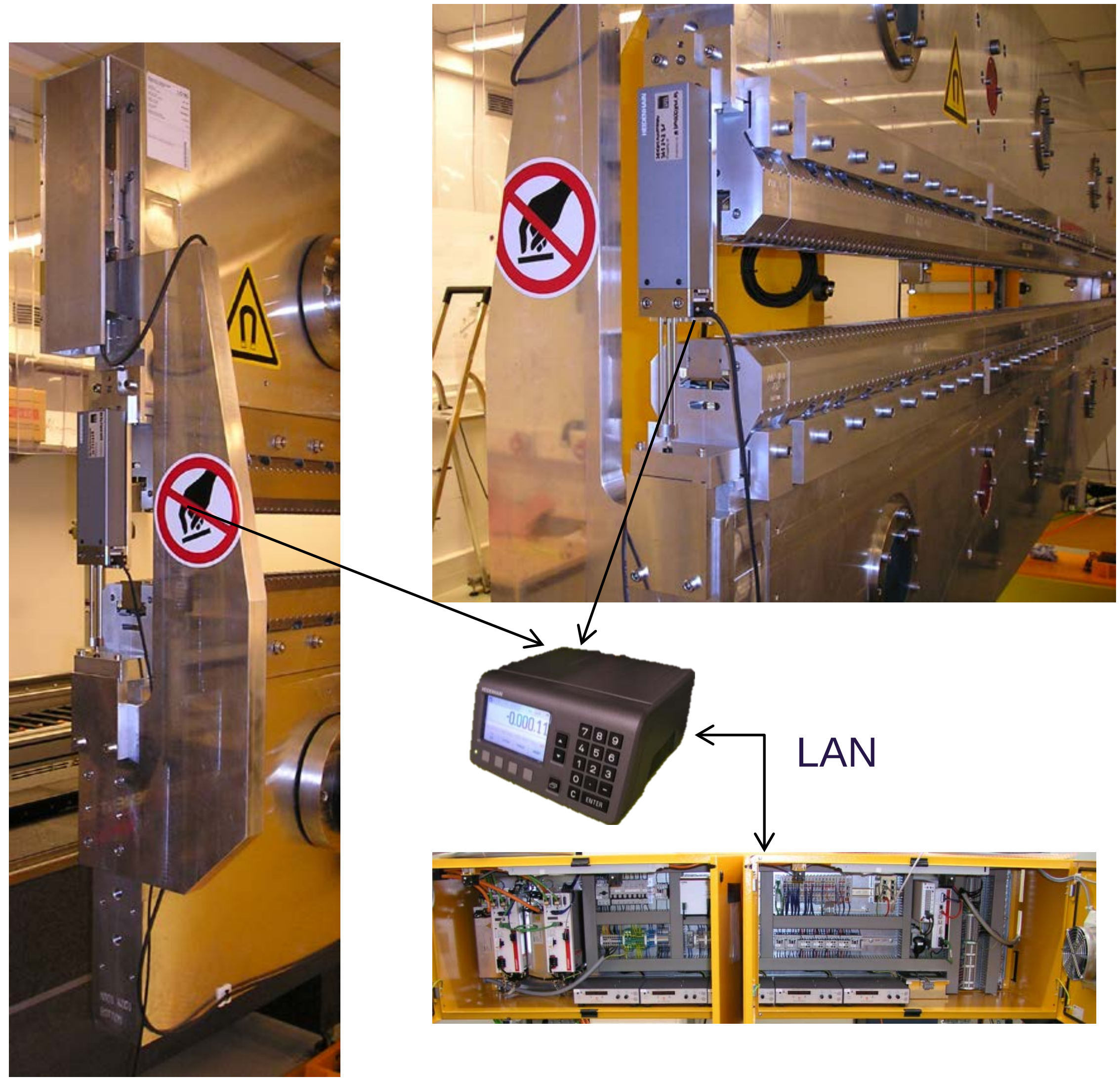
Thank you for your attention!

Enclosure closed

Enclosures opened for SLRS alignment

Adjustment of the linear encoders

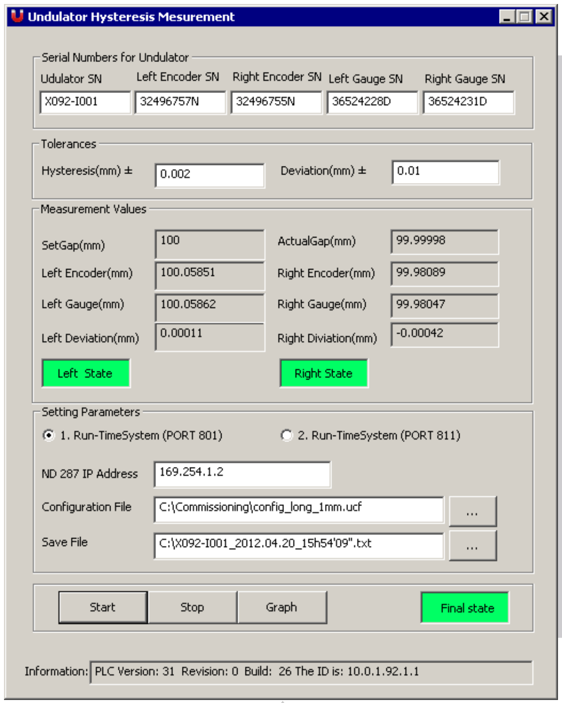


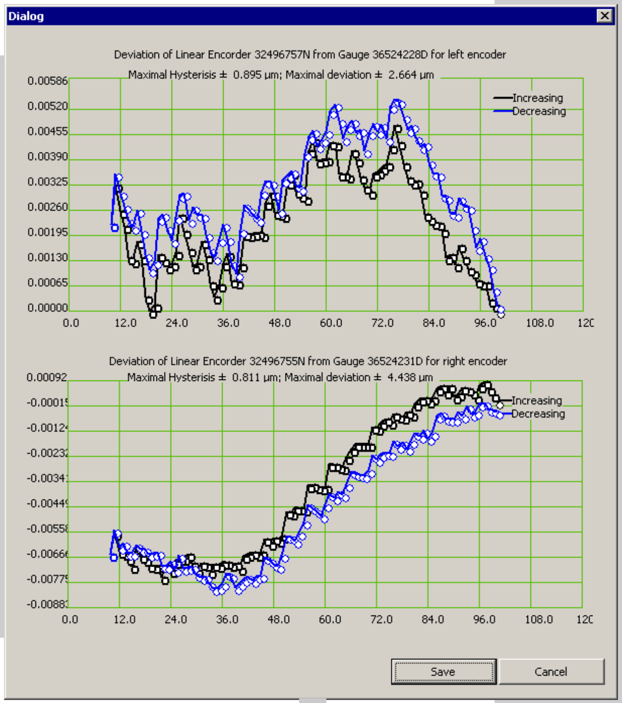


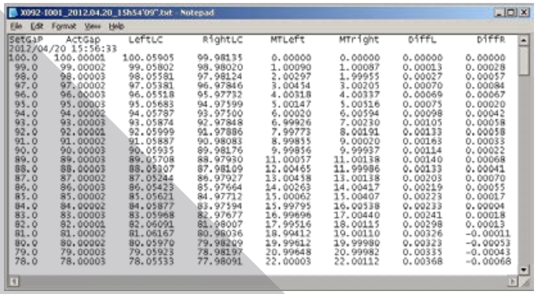
- The installation of a profiled linear guideway has to be validated in order to ensure the requirements of the gap measurement accuracy

Adjustment of the linear encoders

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

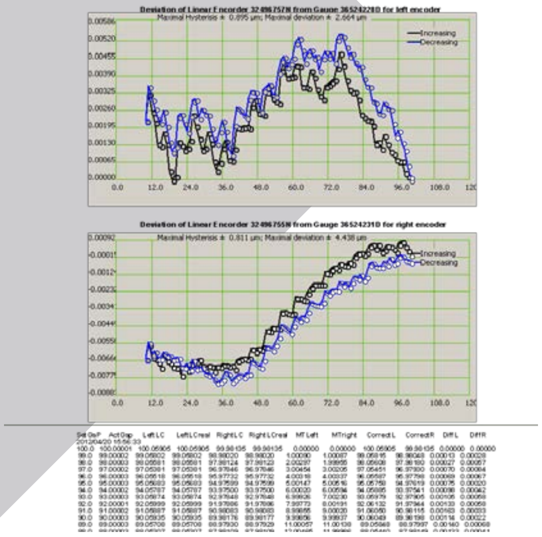




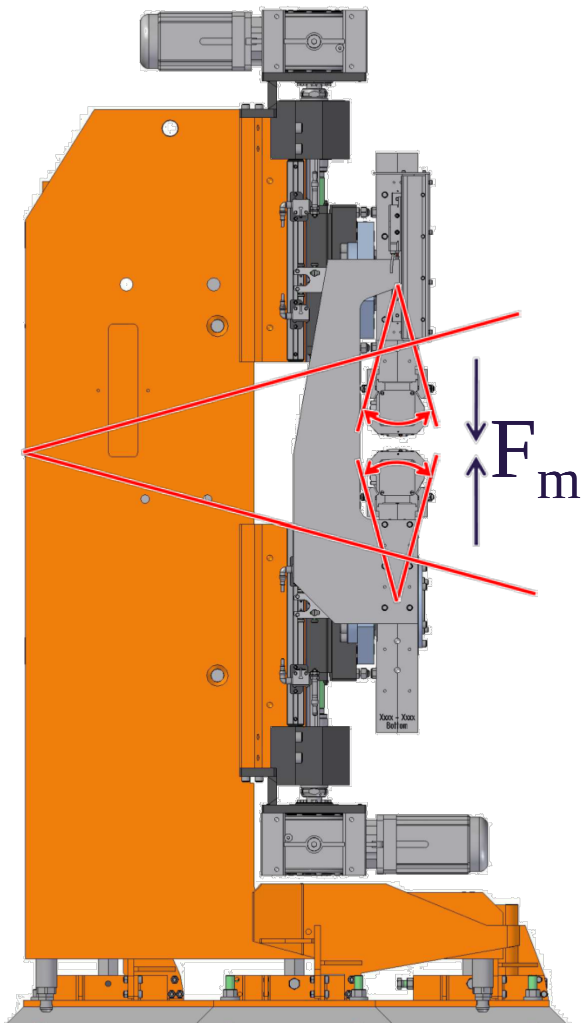

X092-I001_2012.04.20_15h54'09".txt - Notepad

SetGap	ActGap	LeftLC	RightLC	MTLeft	MTright	DiffL	DiffR
2012/04/20 15:56:33							
100.0	100.00001	100.05905	99.98135	0.00000	0.00000	0.00000	0.00000
99.0	99.00002	99.05802	98.98020	1.00090	1.00087	0.00013	0.00028
98.0	98.00003	98.05581	97.98124	2.00297	1.99955	0.00027	0.00057
97.0	97.00002	97.05381	96.97846	3.00454	3.00205	0.00070	0.00084
96.0	96.00003	96.05518	95.97732	4.00318	4.00337	0.00069	0.00067
95.0	95.00003	95.05683	94.97599	5.00147	5.00516	0.00075	0.00020
94.0	94.00002	94.05787	93.97500	6.00020	6.00594	0.00098	0.00042
93.0	93.00003	93.05874	92.97848	6.99926	7.00230	0.00105	0.00058
92.0	92.00001	92.05999	91.97886	7.99773	8.00191	0.00133	0.00058
91.0	91.00002	91.05887	90.98083	8.99855	9.00020	0.00163	0.00033
90.0	90.00003	90.05935	89.98176	9.99856	9.99937	0.00114	0.00022
89.0	89.00003	89.05708	88.97930	11.00057	11.00138	0.00140	0.00068
88.0	88.00003	88.05307	87.98109	12.00465	11.99986	0.00133	0.00041
87.0	87.00002	87.05244	86.97927	13.00438	13.00138	0.00203	0.00070
86.0	86.00003	86.05423	85.97664	14.00263	14.00417	0.00219	0.00055
85.0	85.00002	85.05621	84.97712	15.00062	15.00407	0.00223	0.00017
84.0	84.00002	84.05877	83.97594	15.99795	16.00538	0.00233	0.00004
83.0	83.00003	83.05968	82.97677	16.99696	17.00440	0.00241	0.00018
82.0	82.00001	82.06091	81.98007	17.99516	18.00115	0.00298	0.00013
81.0	81.00002	81.06167	80.98036	18.99412	19.00110	0.00326	-0.00011
80.0	80.00002	80.05970	79.98209	19.99612	19.99980	0.00323	-0.00053
79.0	79.00003	79.05923	78.98197	20.99648	20.99982	0.00335	-0.00043
78.0	78.00003	78.05533	77.98091	22.00003	22.00112	0.00368	-0.00068

Measurement data for Unulator SN X092-I001

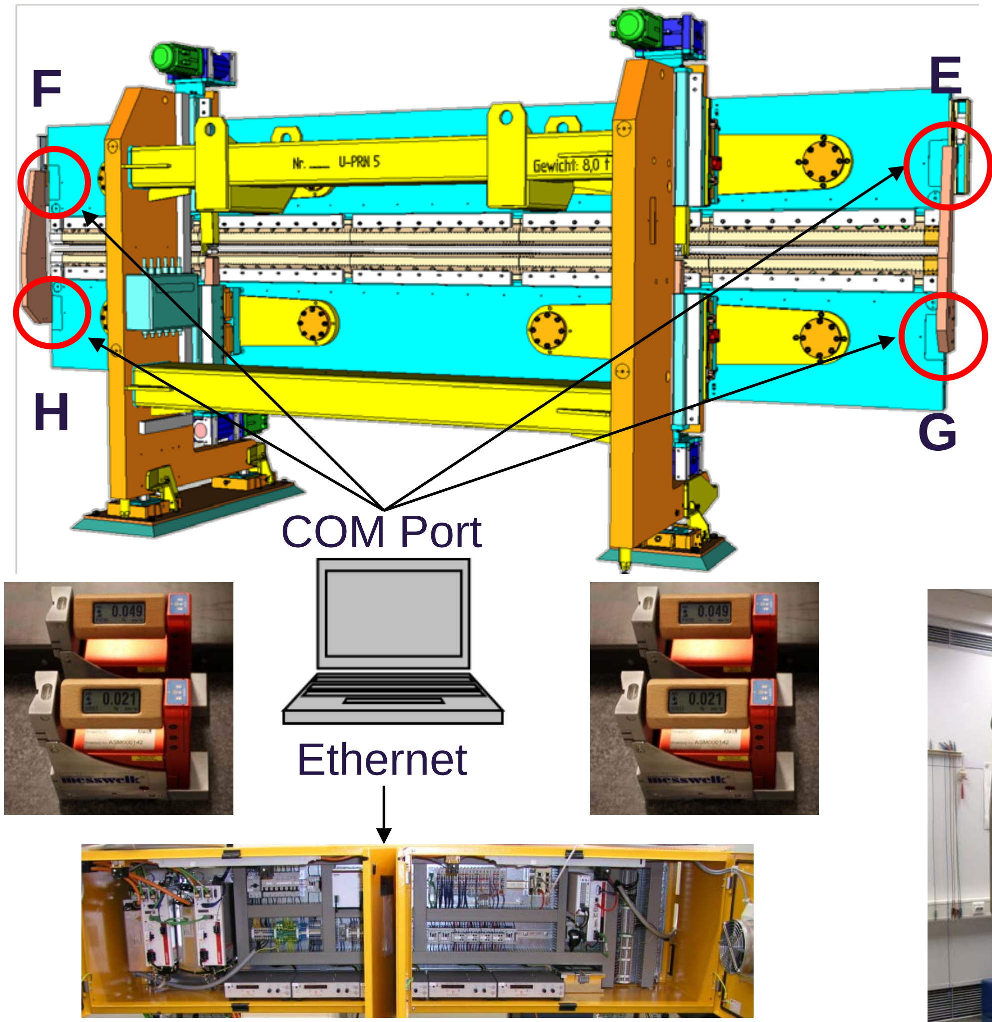


Adjustment of the tilt angle of the girders

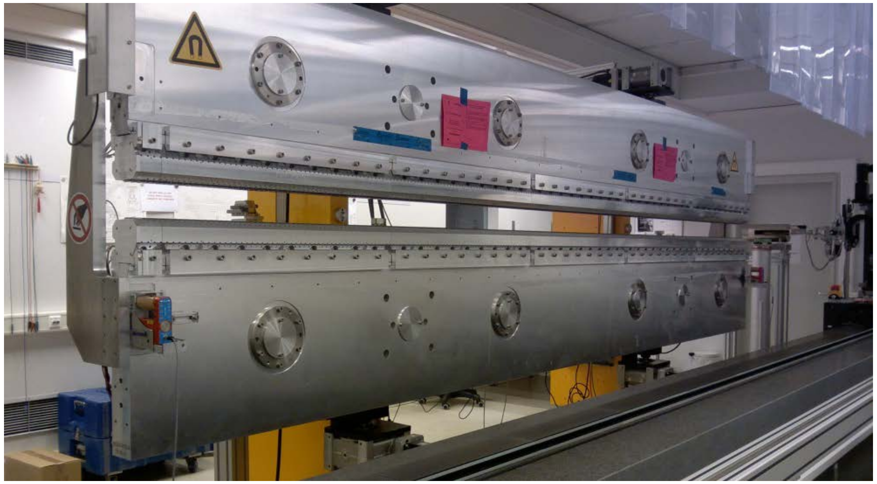


- Due to magnetic force between upper and lower magnet structures the undulator frame bends and the girder tilt angle changes as a function of the undulator gap typically by ±250µrad
- The magnet girders of an undulator have a rotational degree of freedom
- To minimize the influence on the magnetic field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

Adjustment of the tilt angle of the girders

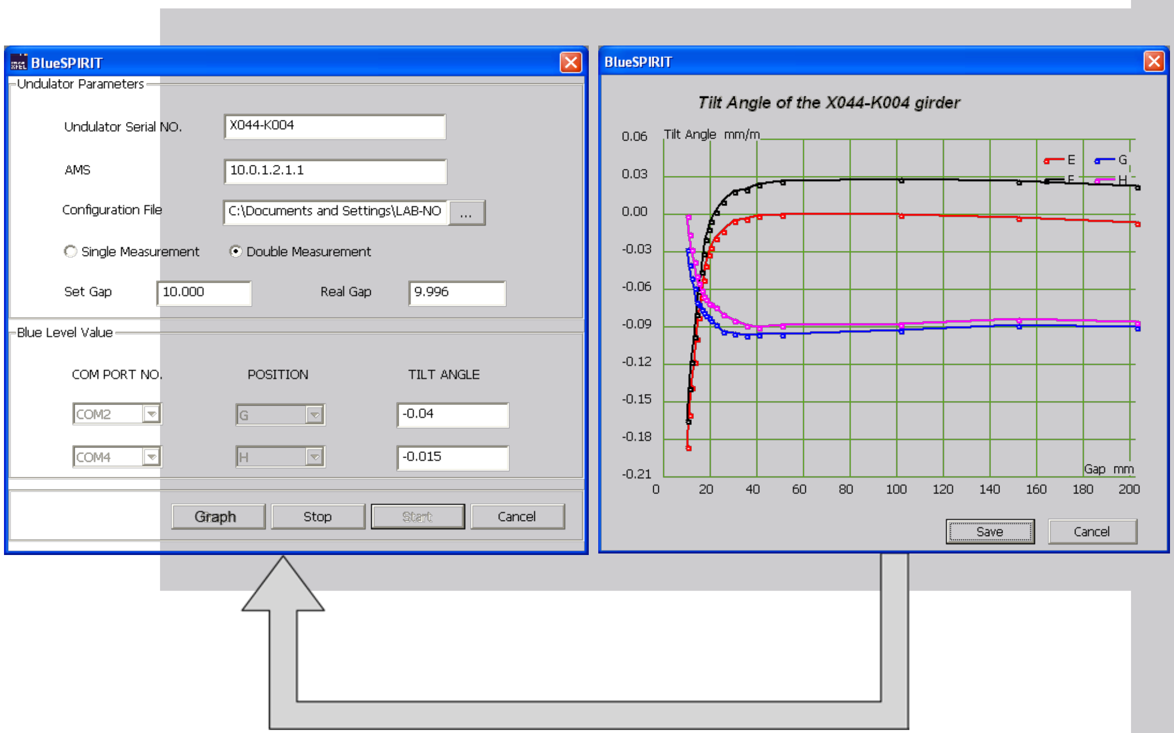


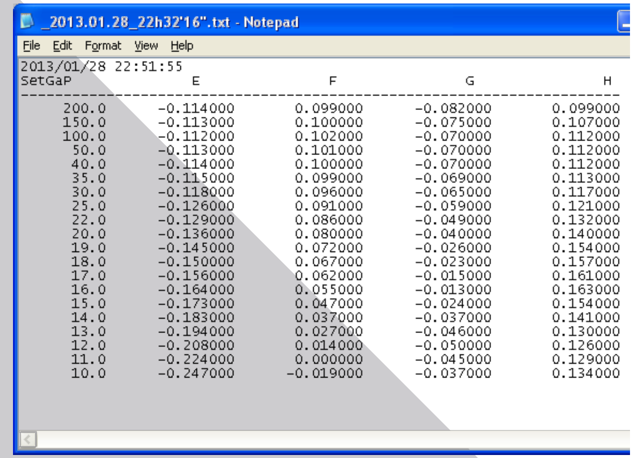
- WYLER's BlueLEVEL high precision electronic inclination measuring instruments are used to measure the angles on four machined reference surfaces of the girders
- The program runs on a separate PC



Adjustment of the tilt angle of the girders

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





_2013.01.28_22h32'16".txt - Notepad

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2013/01/28 22:51:55

SetGaP	E	F	G	H
200.0	-0.114000	0.099000	-0.082000	0.099000
150.0	-0.113000	0.100000	-0.075000	0.107000
100.0	-0.112000	0.102000	-0.070000	0.112000
50.0	-0.113000	0.101000	-0.070000	0.112000
40.0	-0.114000	0.100000	-0.070000	0.112000
35.0	-0.115000	0.099000	-0.069000	0.113000
30.0	-0.118000	0.096000	-0.065000	0.117000
25.0	-0.126000	0.091000	-0.059000	0.121000
22.0	-0.129000	0.086000	-0.049000	0.132000
20.0	-0.136000	0.080000	-0.040000	0.140000
19.0	-0.145000	0.072000	-0.026000	0.154000
18.0	-0.150000	0.067000	-0.023000	0.157000
17.0	-0.156000	0.062000	-0.015000	0.161000
16.0	-0.164000	0.055000	-0.013000	0.163000
15.0	-0.173000	0.047000	-0.024000	0.154000
14.0	-0.183000	0.037000	-0.037000	0.141000
13.0	-0.194000	0.027000	-0.046000	0.130000
12.0	-0.208000	0.014000	-0.050000	0.126000
11.0	-0.224000	0.000000	-0.045000	0.129000
10.0	-0.247000	-0.019000	-0.037000	0.134000