Automation in Commissioning Process of Undulators

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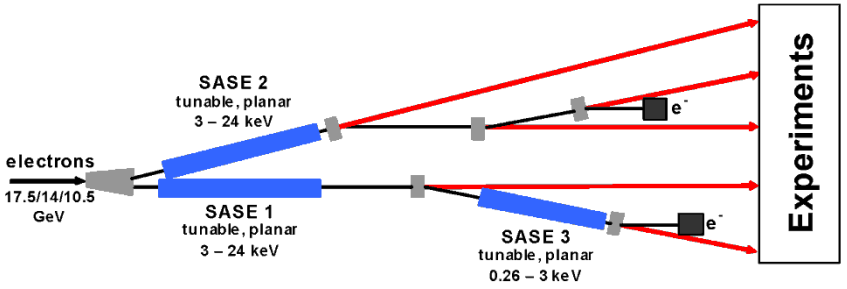
The European X-Ray Free Electron Laser

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



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Objectives

- 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

magnetic measurement

- 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

control system commissioning

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SEMI-AUTOMATED

DURATION ~ 2.5 weeks

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control system commissioning

WERE NOT AUTOMATED

DURATION ~ 2.5 weeks

Basic approach

Initialization
- Connection to the undulator PLC or to external controllers or devices, loading of configuration data

DAQ
- Data acquisition, depending on the configuration data

Processing
- Data processing and analysis

Output
- Formatted output, depending on the task and hardware

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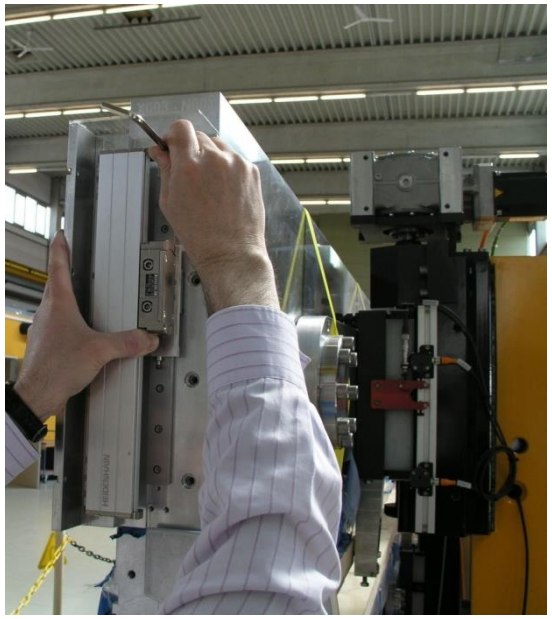
Adjustment of the linear encoders

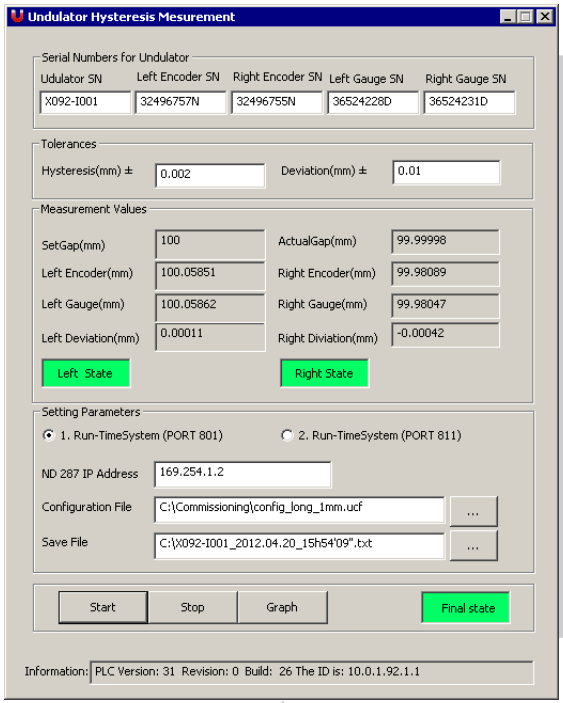


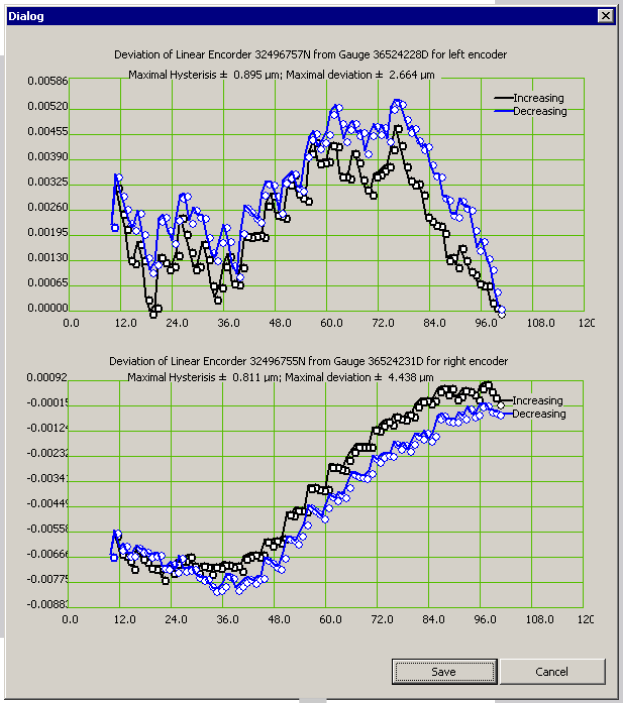
LAN

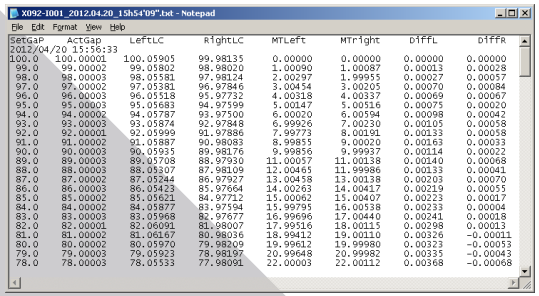
- The installation of a profiled linear guideway has to be validated in order to ensure the requirements of the gap measurement accuracy

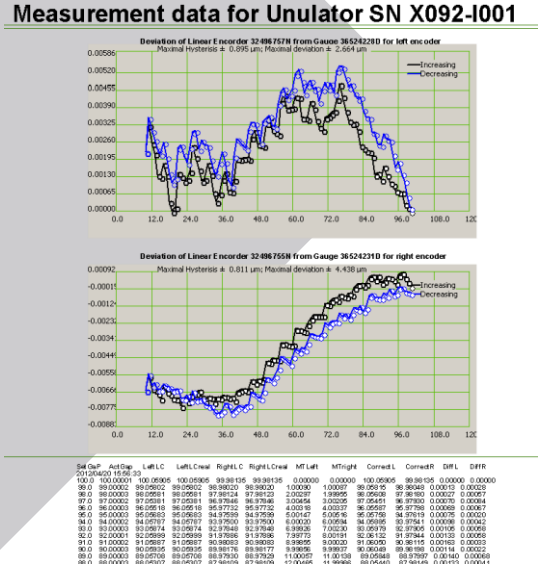
Adjustment of the linear encoders

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

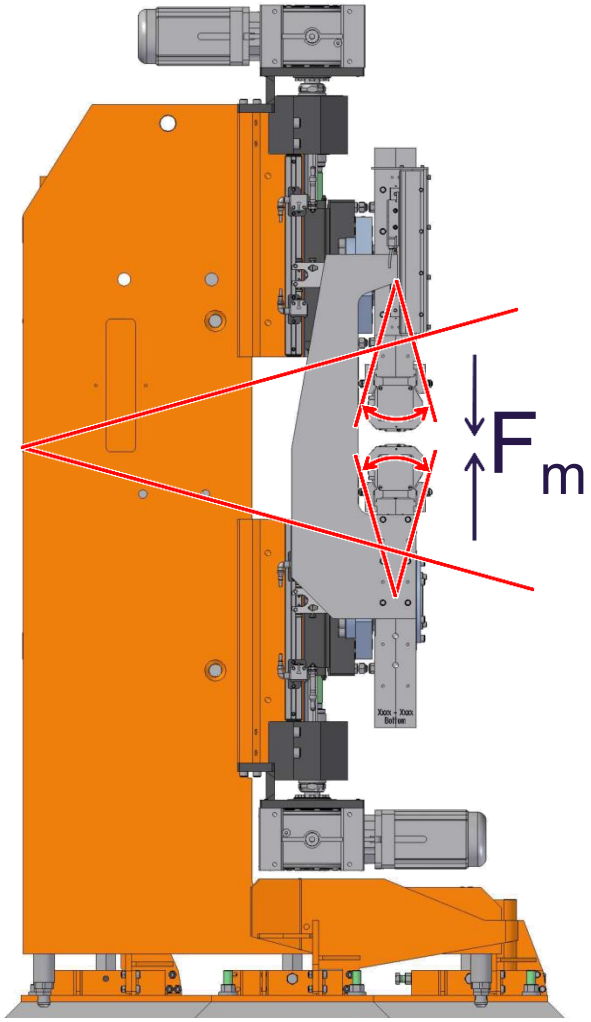








Adjustment of the tilt angle of the girders



- 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

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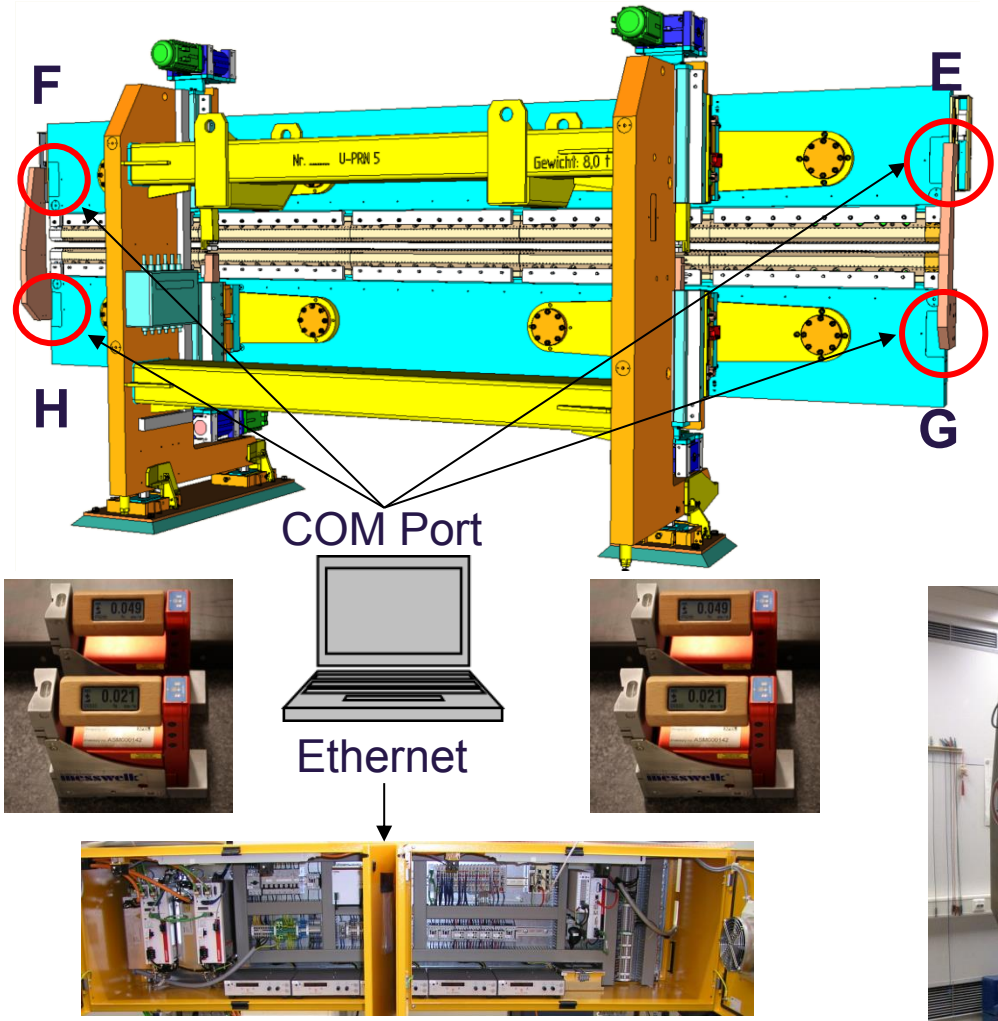
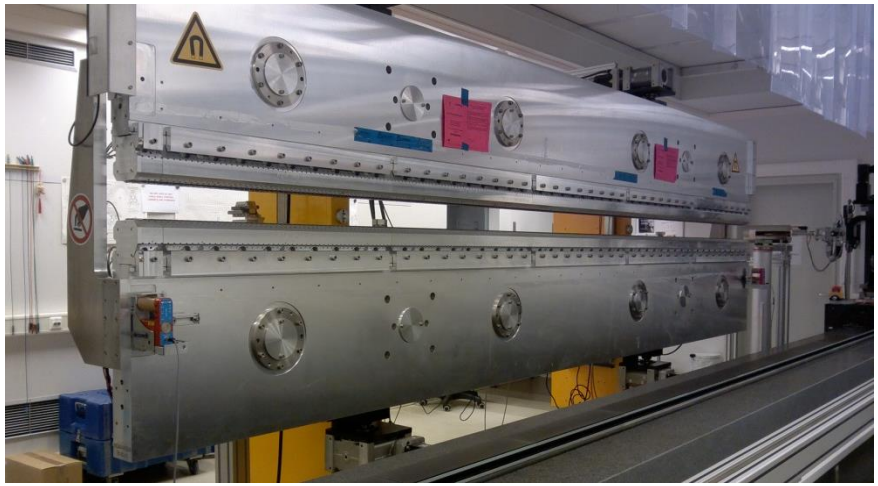
Adjustment of the tilt angle of the girders



- 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



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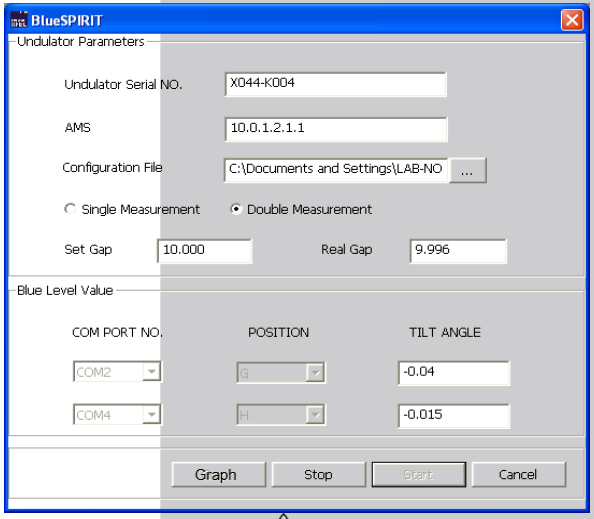
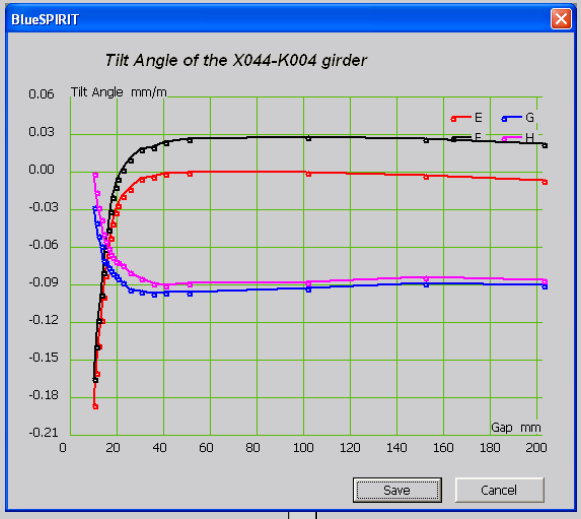
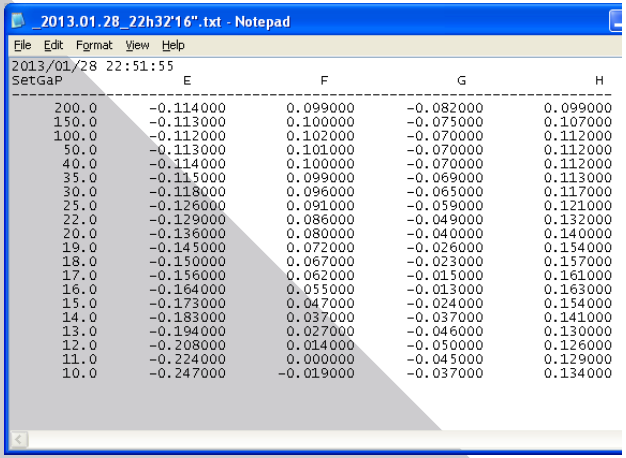
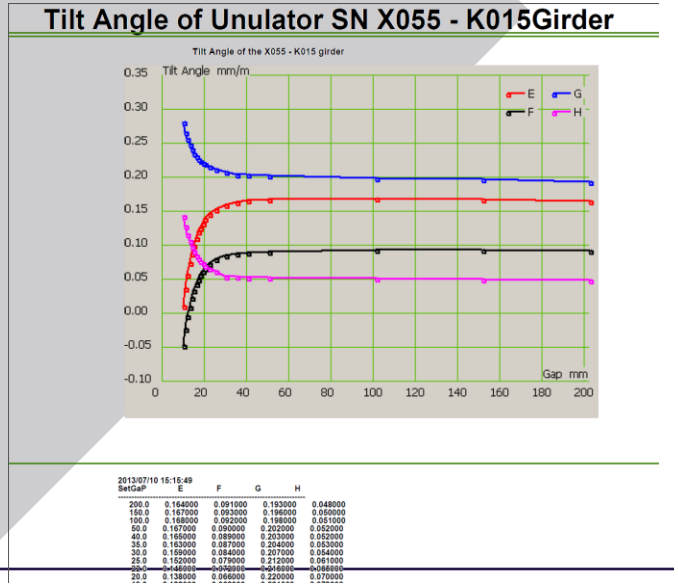
Adjustment of the tilt angle of the girders

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









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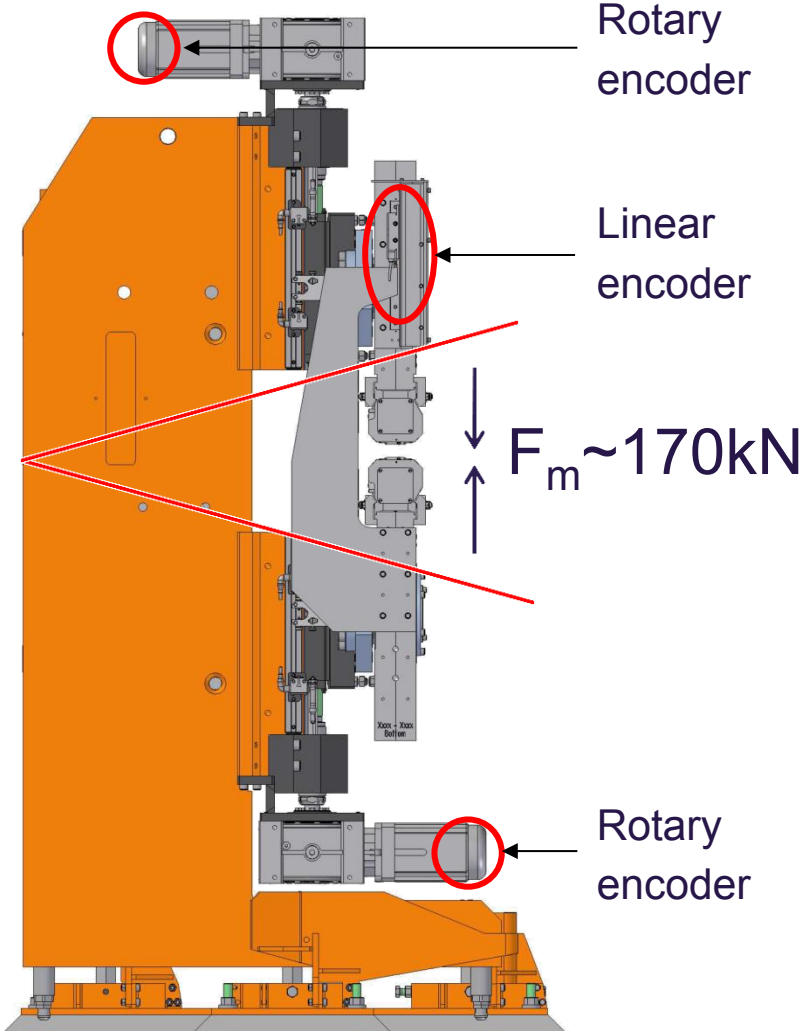
Evaluation of the feedforward correction coefficients



- 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

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Evaluation of the feedforward correction coefficients

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

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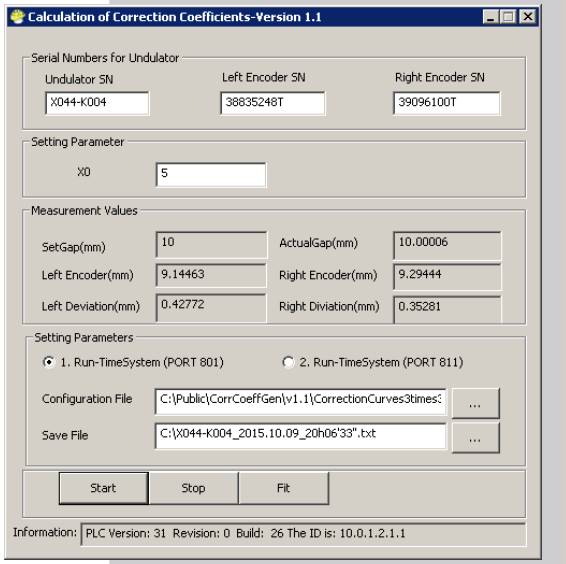
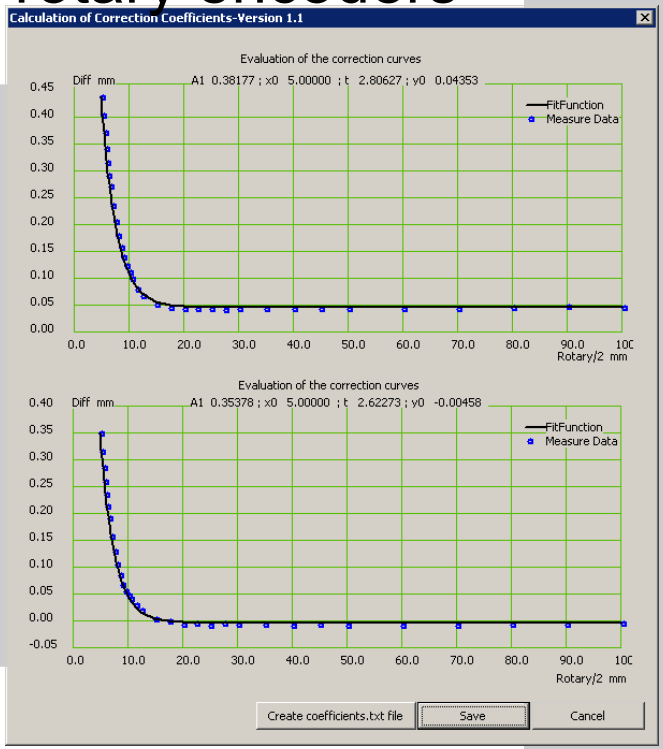
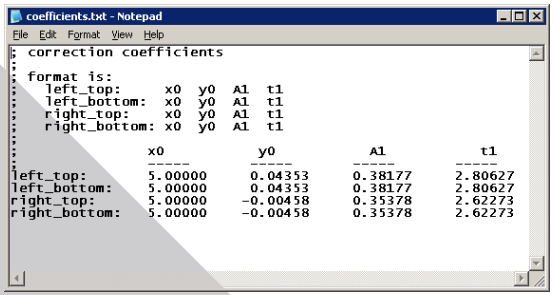
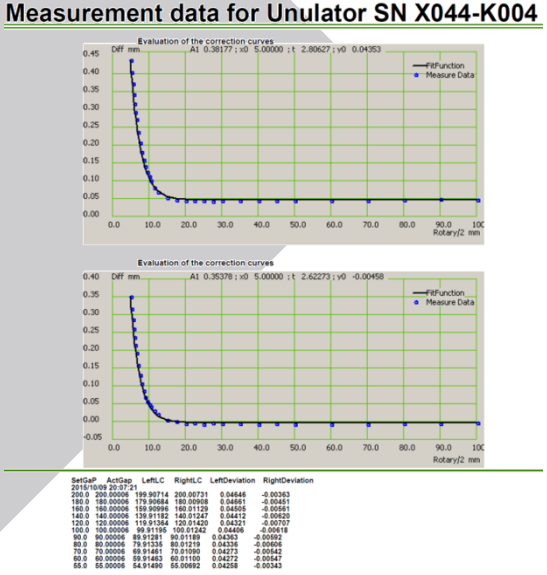
Evaluation of the feedforward correction coefficients

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



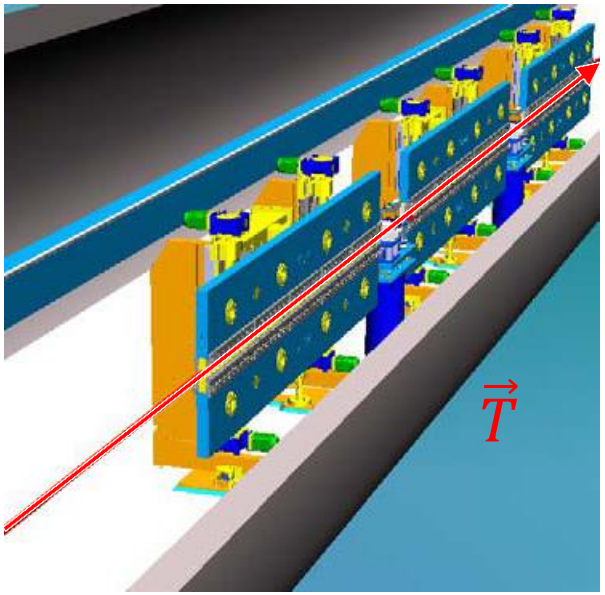






Calibration of temperature sensors for undulator cell

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

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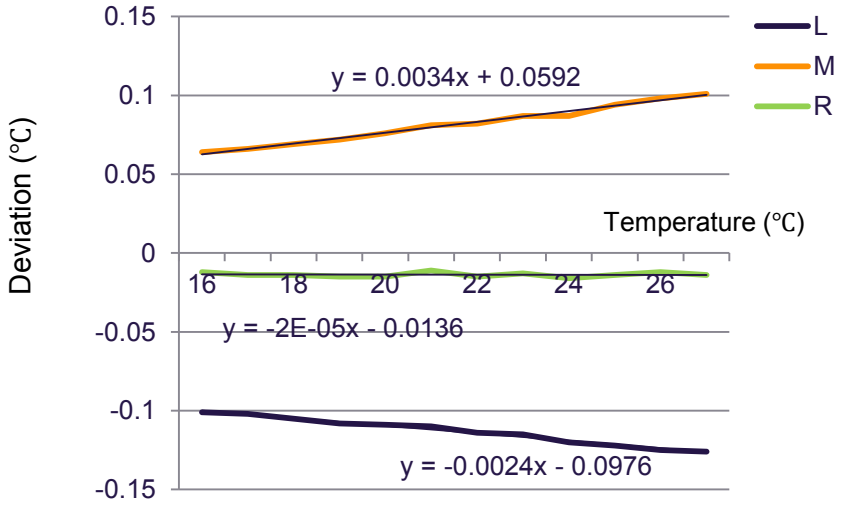
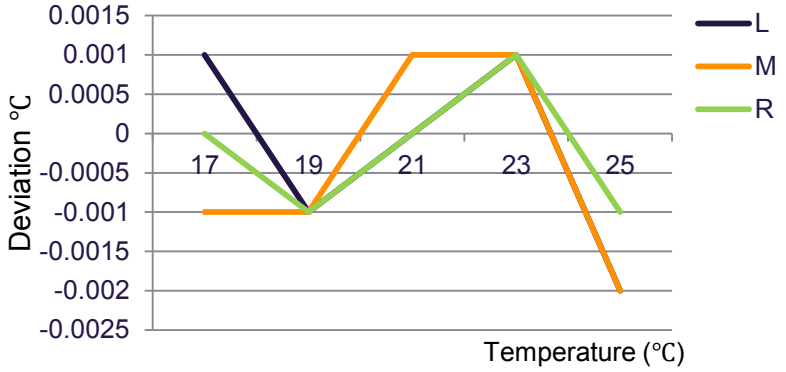
Calibration Method

- All temperature sensors together with a certified reference temperature sensor are thermally connected to an aluminum block and inserted into a thermo-stabilized 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





- The deviation between three sensors is less than ±0.002°C

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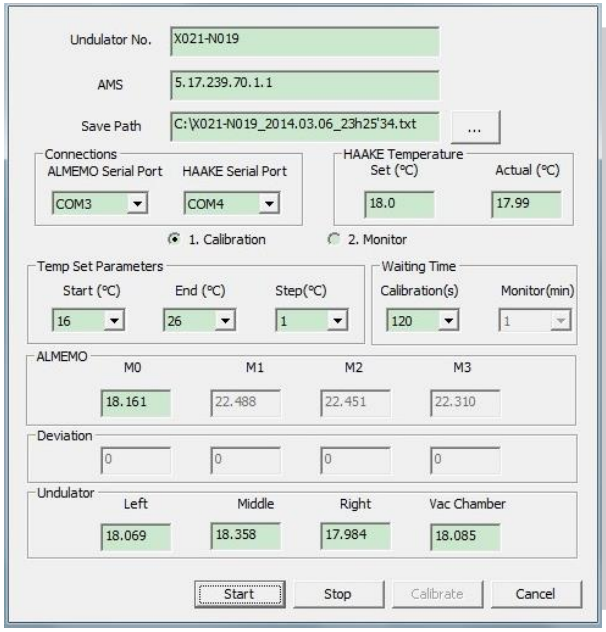
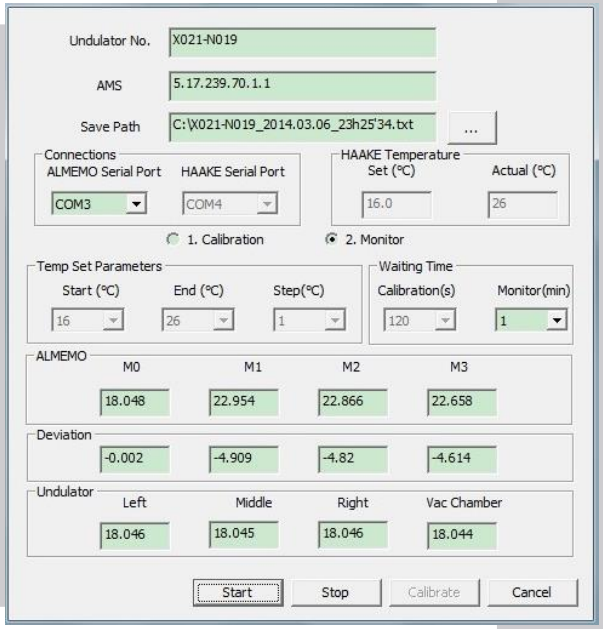
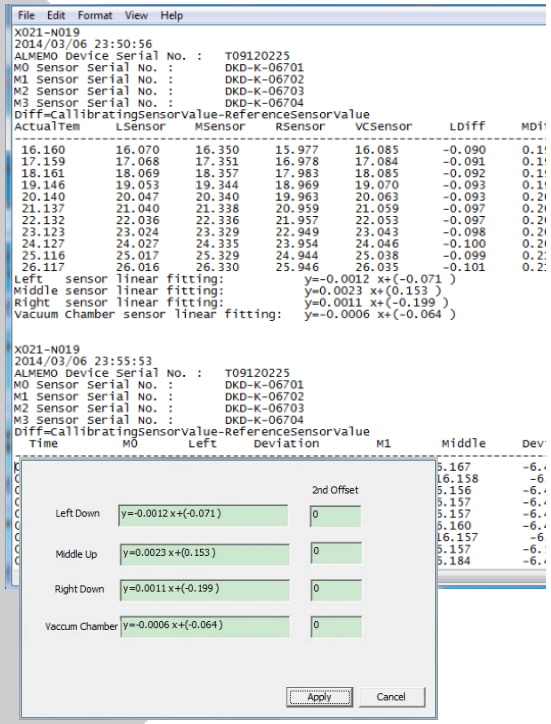
Calibration of temperature sensors for undulator cell

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







- 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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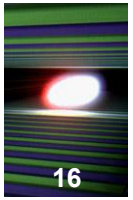
Conclusion



- 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!