THE LOCAL CONTROL SYSTEM OF AN UNDULATOR CELL FOR THE EUROPEAN XFEL

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Abstract

The European XFEL project is a 4th generation light source. The first beam will be delivered in the beginning of 2015 and will produce spatially coherent ≤80fs short photon pulses with a peak brilliance of 10^{32}-10^{34} photons/s/mm^2/mrad^2/0.1% BW in the energy range from 0.26 to 29 keV at electron beam energies 10.5 GeV, 14 GeV or 17.5 GeV [1, 2]. Three undulator systems SASE 1, SASE 2 and SASE 3 are used to produce photon beams. Each undulator system consists of an array of undulator cells installed in a row along the electron beam. A single undulator cell itself consists of a planar undulator, a phase shifter, magnetic field correction coils and a quadrupole mover. The local control system of the undulator cell is based on industrial components produced by Beckhoff Automation GmbH and a PLC implemented in the TwinCAT system. Four servo motors control the gap between the girders on each undulator with micrometer accuracy. One stepper motor is used for phase shifter control, and two other stepper motors control the position of the quadrupole magnet. The current of magnetic field correction coils as well as the gap of the phase shifter are adjustable as a function of the undulator gap. The high level of synchronization (<<1μs) for the complete undulator system (for instance SASE 2 with 35 undulator cells in total) can be achieved due to implementation of a fast EtherCAT fieldbus system in the local control.

SYSTEM OVERVIEW

At the project start-up stage three undulator systems SASE1, SASE2 and SASE3 will be used to produce photon beams (see Figure 1). The electron bunch train is distributed into two branches by a flattop kicker magnet into SASE1 and SASE2 beam lines, where hard X-ray beams are generated. After passing through SASE1 the electron bunches are used a second time by passing through the SASE3 undulator system to create additional soft X-ray beam.

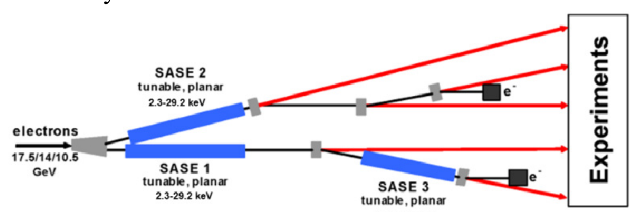

Figure 1: Schematic layout of the electron and photon beam distribution.

The parameters of the undulator systems relevant to the control system are shown in the Table 1 [1-3].

Requirements

The tolerance requirements for the undulator systems relevant to the control system are following [1-6]:

Table 1: Parameters of the Undulator Systems Relevant to the Control System

Photon Beamline	Electron energy GeV	Photon energy keV	Wavelength Å	Gap mm	Magnetic period mm	Quantity of Undulators
SASE 1	10.5	2.3 – 14.9	5.4 – 0.83	10 – 24		
&	14	4.1 – 18.7	3.0 – 0.66	10 – 20	40	35
SASE 2	17.5	6.4 – 29.2	1.9 – 0.43	10 – 20		
	10.5	0.26 – 2.2	47.7 – 5.6	10 – 28		
SASE 3	14	0.47 – 2.6	26.6 – 4.8	10 – 24	68	21
	17.5	0.73 – 4.1	16.9 – 3.0	10 – 24		
						Total: 91

- Undulator gap control accuracy ±1 μm.
- Quadrupole mover positioning repeatability ±1 μm.
- Phase shifter gap control accuracy ± 10 μm.
- Max. Steering Power for Air Coil Correctors ±0.6 Tmm.
- Accuracy of the temperature measurement of magnet structures ± 0.03 K.

The functional requirements to the local undulator cell control are:

- Gap control with low following error (<±10μm).

- Local temperature measurement and appropriate undulator gap correction.
- Undulator gap dependent air coil correction.
- Undulator gap dependent phase shifter control.
- Motion control for quadrupole movers.
- 3 way mixing valve control for the beam pipe temperature stability.
- Safe operation, damage prevention, proper and precise movement limitation, failure detection.

An undulator cell consists of a 5m long undulator segment and a 1.1m long intersection segment (see Figure 2). Four servo motors are used on each undulator to control the gap between girders with micrometer accuracy. One stepper motor is used for phase shifter control, and two other stepper motors control the position of the quadrupole magnet. The current of magnetic field correction coils as well as the gap of the phase shifter are adjustable as a function of the undulator gap.

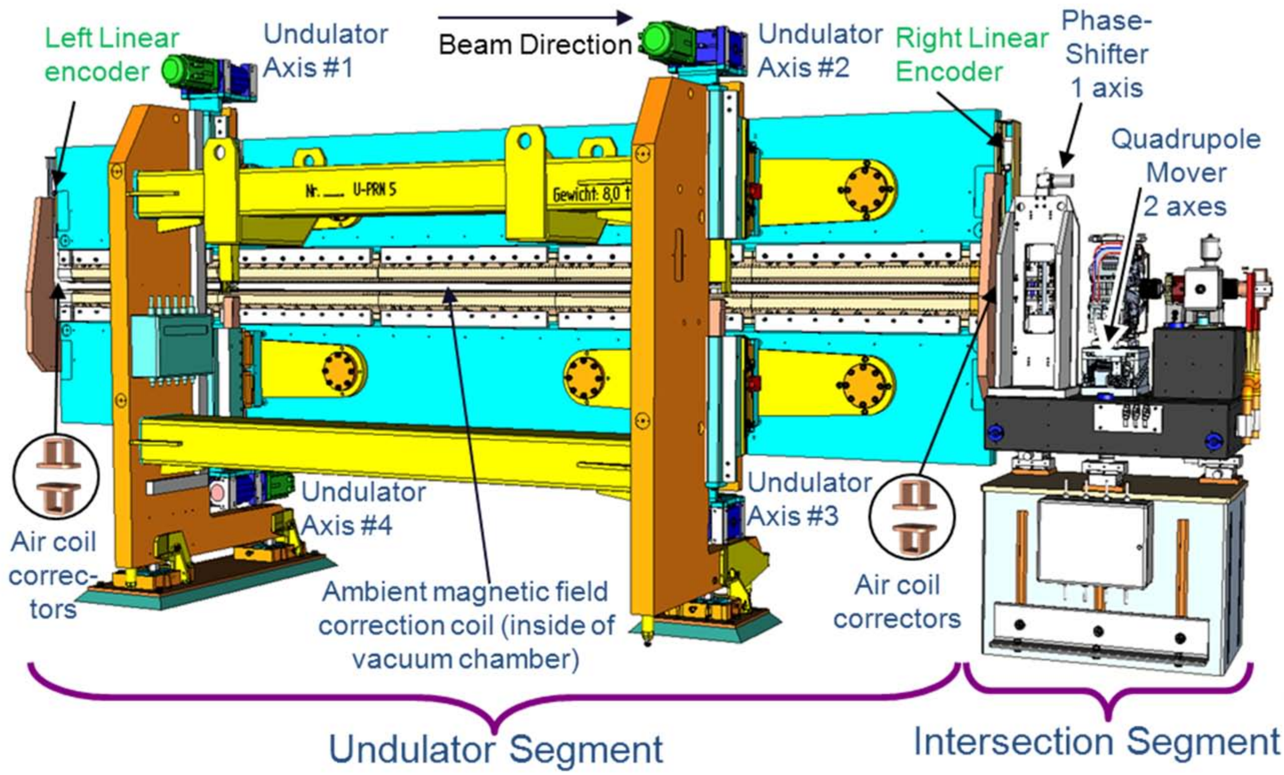

Figure 2: Undulator cell. Undulator and intersection segments in array.

UNDULATOR CELL CONTROL

Control of the Undulator Gap

Each of the four undulator motors is equipped with a rotary multiturn absolute encoder, flanged directly on the axis. In addition to those four encoders each undulator is equipped with two absolute linear encoders, which are installed on both ends of the undulator girders. These linear encoders directly measure the right and left gap between the girders. The undulator can be operated either using rotary encoders or linear encoders as a feedback for the servo drivers. At small gaps the strong magnetic forces cause a deformation of the undulator support frame and thus cause deviations between the linear and the rotary encoder readings. To compensate the influence of these deformations the gap is measured with high precision external gauges during commissioning. The results of these measurements are used to generate curves (see Figure 3) which are implemented as feed forward corrections farther in the PLC program.

If the rotary encoders are used for the gap control, then these correction curves are applied to all four axes.

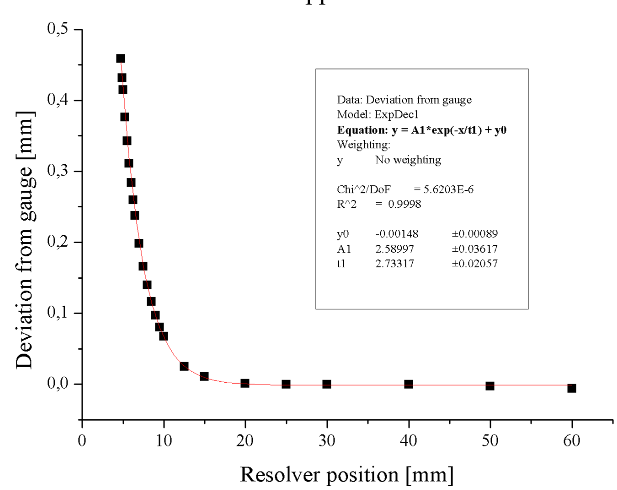

Figure 3: Evaluation of the correction curves for one axis.

In case of using the linear encoders as feedback, the lower two axes are using the corrected value of the rotary encoders as a feedback, while the position of the upper two axes is controlled according to the readings of the linear encoders.

Temperature Drift Compensation

The NdFeB permanent magnet material, which is used to create the magnetic field in the undulator, has a temperature coefficient for its remanent field. These temperature coefficient for the relative magnetic fields $(\Delta B/B)/\Delta T$ in the air gap of the NdFeB dipole magnets is
~ $-1.1\cdot10^{-3}$ K^{-1}. To compensate for magnetic field changes due to temperature variations the gap correction method is used [4]. The required gap correction is calculated in the PLC program. The correction is done according to equation 1:

$$\Delta g_{Loc} = \frac{\lambda_U \eta}{b + 2cg / \lambda_U} \Delta T_{Loc} \tag{1}$$

where $\Delta T_{\mathrm{Loc}} = T_{\mathrm{Nom}} - T_{\mathrm{Loc}}$, T_{Loc}, is the local temperature, T_{Nom} is the nominal operating temperature of the undulator system, λ_U is the undulator period length, g the undulator gap, η is the reversible temperature coefficient of NdFeB ($-1.1\cdot10^{-3}$ K^{-1}), b and c are empirical constants describing the gap dependence of the peak field.

At 10mm gap, for instance, the temperature dependence for SASE 1 and SASE 2 is ~9.17µm/K, for SASE 3 this dependence is ~15.7µm/K [5].

To provide accurate temperature data three PT100-3 sensors are mounted inside the magnetic structures, one in the middle of the upper structure and two on both edges of the lower structure. The temperature is measured by Almemo 8590-9 Delta-sigma, 24-bit A/D converter.

Control of the Temperature of Vacuum Chamber

In order to avoid bending of the magnet girders by temperature gradients the temperature of the vacuum chamber should not differ from that of the girders. Thermal stabilization is achieved through the cooling water by appropriate mixing of warm (27°C) and cold (18°C) water with 3-way valve. The actual water temperature of the 3-way valve outflow is measured by PT100-3 sensor, which is connected to the same Almemo 8590-9 temperature measuring device, and provides feedback to the PLC program. In the PLC program the water temperature and the temperature of magnetic structure are compared and 3-way valve is controlled to eliminate any deviation.

Magnetic Field Corrections by Means of Air Coils

On each undulator segment two horizontal and vertical air coil correctors are used.

- to compensate residual gap dependent steering errors of the undulator (~ ± 0.1 Tmm),
- to compensate residual gap dependent steering errors of the phase shifter (~ ± 0.05 Tmm),
- for beam ballistic steering of ± 0.45 Tmm

The maximal steering power in horizontal and vertical direction is therefore ±0.6 Tmm.

During operation the air coil correctors are controlled using look up tables. These look-up tables contain the steering strengths as a function of the undulator gap, which are required to compensate 1st and 2nd field integral errors. They need to be derived from magnetic measurements. The required correction currents are calculated from the conversion constants which are in the range 0.4 to 0.67 Tmm/A.

An ambient magnetic field correction coil consisting of just two parallel wires is fitted inside two bores of the vacuum chamber. It's called Two Wire Corrector (TWC). It can be used for compensation of an ambient magnetic field of up to 150µT.

The current for each air coil and the TWC is regulated by means of constant current power supplies controlled via analog output terminals. Direction of the magnetic field is changed by means of polarity reversal relay, which is changing the current direction supplied to the air coil.

Phase Shifter Control

For gap adjustable undulator systems phase shifters are need to adjust the phase between electrons and photons field. The phase shifter for European XFEL is based on permanent magnet technology. The magnet structure consists from four magnetic arrays, two in the top and two in the bottom. The phase is adjusted by changing the gap between upper and lower magnetic arrays. Figure 4 shows the dependence of the phase shifter gap value on the undulator gap value for SASE 2 and SASE 3 at different harmonic numbers [6]. The basic control requirement is that the phase shifter gap has to follow the undulator gap.

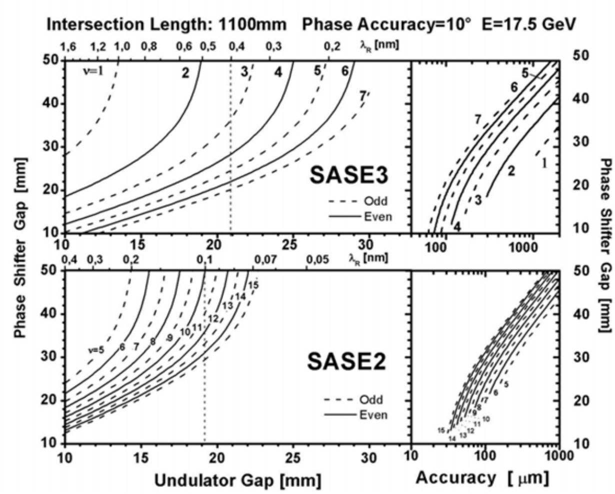

Figure 4: Tuning curves for the phase shifter. The right-hand side graphs show the required gap precision of the phase shifter for to control the phase within ±10°.

The phase shifter is controlled by means of a look up table, which is evaluated from the magnetic tuning curves. Both motion controls, undulator and phase shifter, are synchronized with a following error of ≤10µm.

Motion control for the phase shifter consists of a five-phase stepper motor, a self-locking gearbox with a ratio of i=50, a spindle with right- and left-handed thread with 5 mm pitch, and an incremental linear encoder for position feedback (see Figure 5).

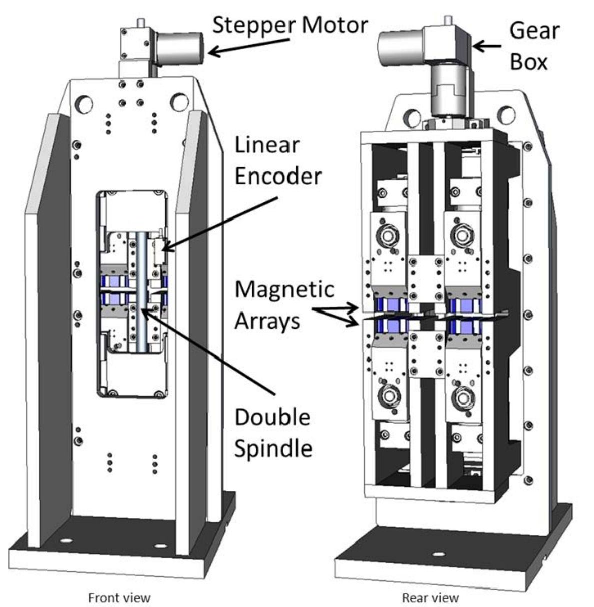

Figure 5: Motion control components of the phase shifter.

Quadrupole Mover Control

The control of the quadrupole magnet movers that are situated between undulator segments is a part of the local undulator control system as well. Information about the quadrupole magnet corrections or the set values in horizontal and vertical directions is obtained from the beam positioning system. This information is received by undulator local control from the accelerator control via the global undulator control system. The requirements to the quadrupole mover control are the following:

- Movement range in horizontal and vertical directions: ±1.5 mm.
- Positioning repeatability in both directions: ±1µm.
- Maximal movement speed in both directions: 1mm/sec.
- Maximum load: 75kg

The quadrupole mover control consists of two actuators for horizontal and vertical movement, driven by five-phase stepper motors and two LVDT sensors as feedback for each motor.

Implementation

The local control system of undulator cell is completely implemented in Beckhoff's PLC and TwinCAT system manager.

The graphical user interface (GUI) consists of following windows:

- Main control window.
- Intersection control.
- Alarm display.
- Axes status.
- System information.

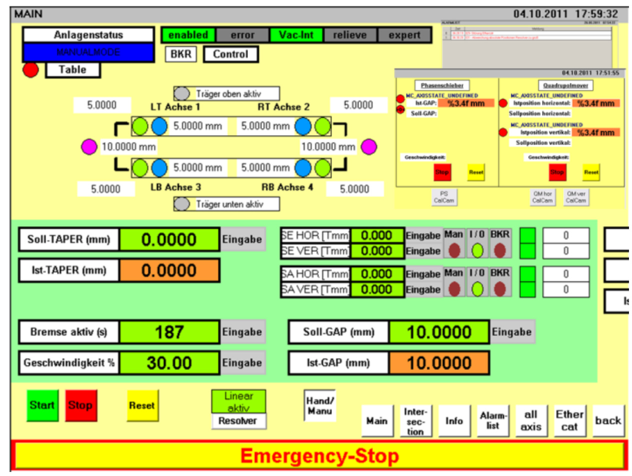

Figure 6: GUI widows of the local control for the undulator cell.

The local control system provides all possibilities for control, monitor and error tracing of each undulator cell. It also provides the interfaces to integrate the local control system into the global undulator control system.

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