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CONCEPTUAL DESIGN REPORT

Undulator Control Systems

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Abstract

The European XFEL is a fourth-generation light source. The first beam will be delivered at the beginning of 2015. The facility will produce spatially coherent photon pulses with a duration of less than 80 fs and 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 29.2 keV at electron beam energies of 10.5 GeV, 14 GeV, or 17.5 GeV.

Three undulator systems are used to produce the photon beams. Each undulator system consists of an array of up to 35 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. Undulator systems are of central importance for the generation of the X-ray free-electron laser (FEL) radiation.

This report describes the conceptual design of the entire undulator control system including local and global control. It presents a concept of integration of the undulator control into the accelerator control system as well as into the experiment control system.

1 Introduction

Undulator systems for X-ray FELs are long complex systems with many control parameters, such as moving axes and control currents. For the systems of the European XFEL, these might sum up to 300–400 control parameters, which need to be changed in a coordinated fashion. Such a control system is unique and has never been built before. During the past decade, there has been a strong development in industrial automation and control technology using field bus systems, which became quite reliable, economic, and widely used. The control systems for the European XFEL undulator systems take advantage of these developments and are based on industrial components.

The purpose of this report is to present the entire concept of the undulator control system for the European XFEL.

2 System overview

2.1 General description

The European XFEL is using the principle of "self-amplified spontaneous emission" (SASE) in the photon energy range of 0.26 to 29.2 keV [1]. The startup configuration includes three undulator systems called SASE1, SASE2, and SASE3. They are all built in underground tunnels. The layout is shown schematically in Figure 1. The electron beam comes from the left and is distributed into two branches by a flat-top kicker magnet. One branch comprises SASE1 and SASE3. The other branch is serving SASE2 only, but provides space for future extension with two more undulator systems. The tunnel layout of the SASE2 undulator system is shown in Figure 2.

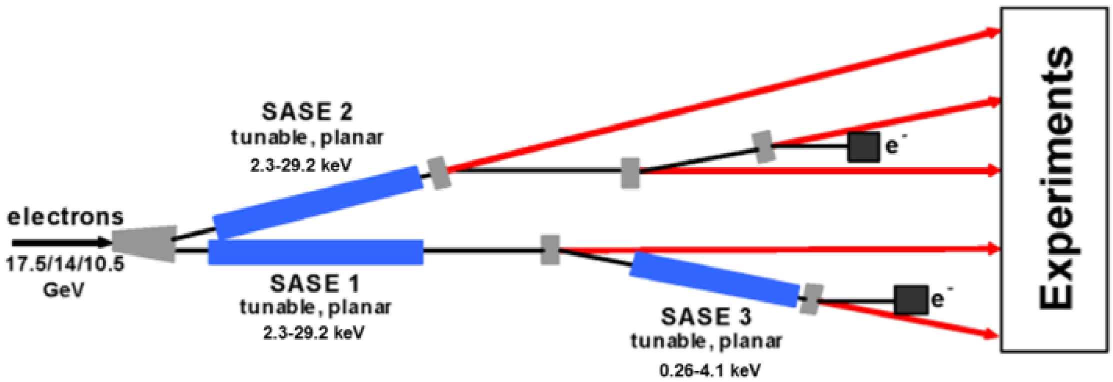

Figure 1: *Schematic layout of the electron and photon beam distribution*

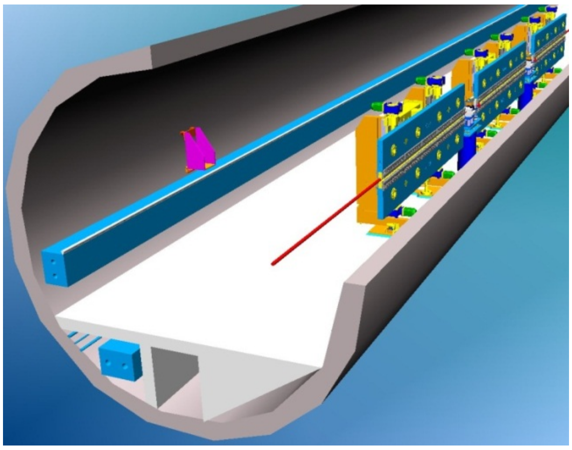

__Figure 2:__ Arrangement of the SASE2 undulator system in the tunnel

An undulator system as shown in Figure 2 is a periodic array of undulator cells. A cell consists of a 5 m long undulator segment, sometimes simply referred to as “undulator”, and a 1.1 m long intersection (Figure 3).

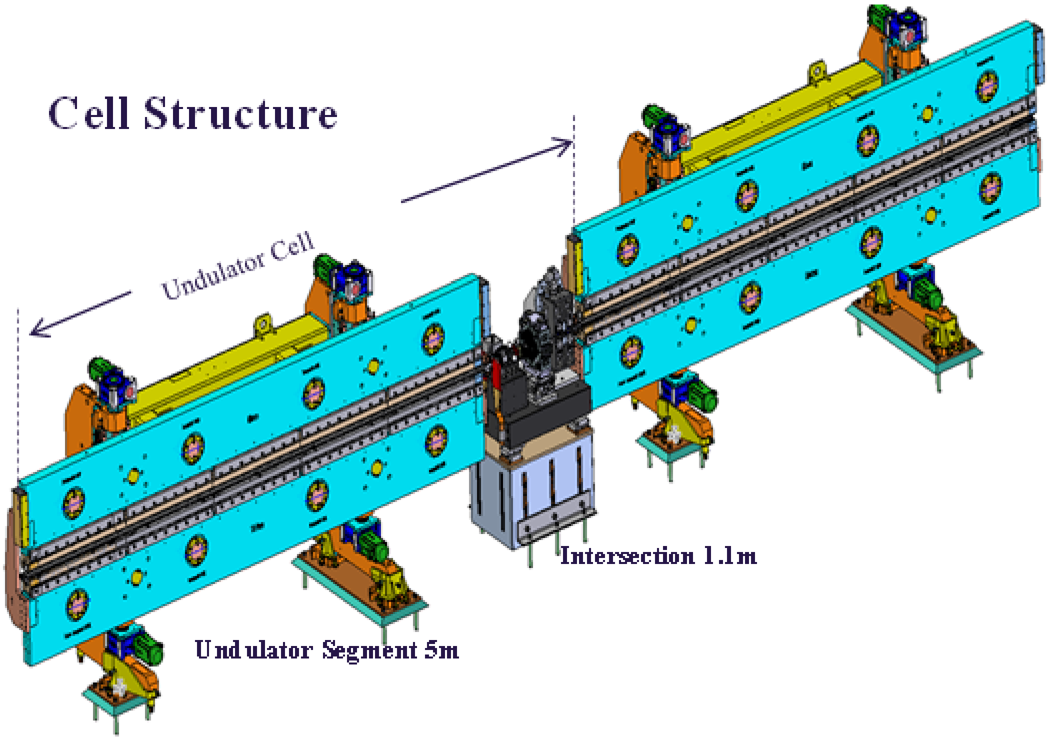

__Figure 3:__ Cell structure of the European XFEL undulator systems

SASE1 and SASE2 are optimized for the hard X-ray range from 4 to 29.2 keV. In order to do so, 35 cells are required. In contrast, SASE3, which is using the spent beam from SASE1, is serving the soft X-ray range from

0.26 to about 2 keV and therefore needs only 21 cells. Key parameters of the undulator systems are reproduced in Table 1 [1].

The hardware of all undulator segments and intersections is strictly standardized and to a large extent identical. Only the period lengths differ as shown in Table 1.

Table 1: *Parameters of the undulator systems relevant for the control system*

Photon beamline	**Electron energy [GeV]**	**Photon energy [keV]**	**Wavelength [Å]**	**Gap [mm]**	**Magnetic period [mm]**	**Number of undulators**
SASE1	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
SASE2	17.5	6.4–29.2	1.9–0.43	10–20		
	10.5	0.26–2.2	47.7–5.6	10–28		
SASE3	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

The intersections contain important elements for the operation: quadrupoles and quadrupole movers for electron beam focusing and steering, beam position monitors, vacuum pumps, air coil correctors for the undulator segments and the phase shifters. Their function and control will be explained in detail later in this report.

2.2 Industrial hardware concept

For FEL operation, a large number of components have to be controlled. This is the task of the undulator control system. Such a system and its control have never been built and are unique.

Fortunately, in the past decade, there has been a strong development in industrial automation technology using field bus systems, such as EtherCAT, CANbus, Profibus, and so on, which facilitate the solution of complex control and motion control problems.

Their properties and capabilities include:

- Closed-loop servo control of motors of practically any size.
- Hardware flexibility: almost all position measurement devices available on the market, such as absolute or incremental, linear or rotary encoders, linear variable differential transformers (LVDTs), and so on, can be used and integrated as the critical part of a feedback loop, i.e. for the measurement of the actual position.
- Camming, meaning that one or more axes and/or output voltages and output currents are changing as a function of another. The functional relationship can be defined externally, i.e. by lookup tables or parameters of analytic functions.
- Correction tables can be included, which correct systematic positioning errors. Errors need to be reproducible, measured and known. Then the corrections can be used as a feed-forward signal.
- Synchronization of multiple axes.
- Complex systems can be programmed to specific requirements, including monitoring of operational safety.
- Use of high-speed field bus systems.
- Availability of a large variety of control components, such as ADCs, DACs, I/Os, encoder interfaces, motor controllers, etc.
- Cost-economic solutions. Many components are available with short delivery times, off the shelf.

During the last years, industrial automation components have been used more and more for the control of accelerators and scientific experiments.

2.3 Functional description

2.3.1 General requirements

For fixed electron energy, the radiation wavelength of an FEL is only determined by the gap of the undulator system, whereby a slight gap increase along the undulator system, also called “taper”, might be applied to account for energy losses of the electron beam by the FEL process. This gap increase simultaneously optimizes the emitted radiation power. The above-mentioned mode sets basic requirements for the undulator system operation. In addition, fast tuning of the radiation wavelength is highly desirable for many spectroscopic techniques requiring fast variation or scanning of the radiation wavelength, which is set by the gap of the undulator system. Dynamic control of the undulator gap is therefore of great importance for user operation.

The maximum speed of gap change, as allowed by the motors, is about 10 mm/s. For operation with “beam ON”, however, a severe physical limit is set by eddy currents in the poles of the undulator. According to Lenz’ law, eddy currents counteract all field changes. The proper time-independent steady-state field is obtained only after they have decayed. Eddy currents impose a speed limit on gap change, which has to be found empirically, but is expected to be ≤ 1 mm/s. However, for the selection of the control hardware, speed was of no relevance since all components were compliant even with the highest possible speed, without additional expenses. So the decay time for eddy currents defines the speed limits of gap change.

Tuning the gap of an undulator system thus requires a fast, dynamic change of the gaps of the individual segments, and changing the corrector coils and phase shifters in a well-defined and synchronized fashion. In total, for an undulator system consisting of 35 cells, 350 axes have to run synchronously. This requires the selection of the appropriate software and hardware components.

A first concept for an undulator control system for an X-ray FEL was already proposed in 2000 in [2] within the framework of the TESLA-XFEL design report. Many aspects of this basic concept are still valid. First developments of the control systems for the European XFEL date back to 2005. In a synergetic R&D effort between the PETRA III project at Deutsches Elektronen-Synchrotron (DESY) and the precursor project of the European XFEL, a concept for a local control system based on hardware by Beckhoff GmbH was developed. In the following years, it was applied to the undulators of PETRA III and successfully tested and improved. This concept has been further developed and now serves as the basis for the local control of a European XFEL undulator cell. However, several extensions and modifications for X-ray FEL operation are required. This will be explained below.

2.3.2 Cell controls

The undulator cell as described above is the elementary unit of an undulator system. Here, the following movements and controls are needed:

- Four motors are used to change the gap of an undulator segment. This requires synchronized movement in closed-loop feedback with μm accuracy. The following error should be ≤ 10 μm over the full gap range from 10 to 200 mm. Ultimate gap control accuracy should be better than ±1 μm.
- Five air coil correctors provide proper correction of the residual field errors of the undulator segment and control of the first and second field integral, as well as of the vertical ambient field component. This is done by means of five power supplies. For the current settings of these power supplies, lookup tables as a function of gap need to be provided, which have to be derived from magnetic measurements. These corrections are very specific functions of the gap of an undulator segment. They have the form:
  $$I_n = f_n(gap_{\mathrm{Und}})$$
  where *n* denotes the n^{th} power supply current I_n.
- In a similar fashion, the phase shifter gap is set such as to provide the proper phase advance of the emitted radiation of a multiple of·2π over the whole cell. This requires the movement of the phase shifter gap, which is actuated by a single motor, to be synchronized with the undulator gap:
  $$gap_{\mathrm{Phase\ Shifter}} = f(gap_{\mathrm{Und}})$$
  This functional relationship has to be established again through magnetic

measurements. In general, it includes specific properties of a phase shifter and of the undulator segment.

Gap changes should be as fast as possible. This means that all axes and currents need to be changed dynamically, i.e. while on the move.

In addition, in each cell, there are three tasks not related with gap movement:

- For beam steering, the quadrupole centre needs to be moved in the two transverse directions using the two axes of the quadrupole mover. The required position repeatability of the hardware is ±1 μm. This implies closed-loop movement with sub-micrometre resolution.
- The temperature distribution of the undulator segment needs to be monitored with an absolute accuracy of ±0.03 K.
- To avoid any induced transverse temperature gradient in the 5 m long girders of the undulators, the temperature of the vacuum chamber needs to be adjusted exactly to the measured temperature of the environment. This is accomplished by mixing water with 18°C and 27°C with the help of a controlled three-way valve to an accuracy of ±0.1 K.

This section only gives an overview. All details are described in the following sections.

2.3.3 Global controls

The complete undulator system is controlled by the global control system. Its architecture reflects the cell structure of the hardware in the tunnels.

1. The global control system ensures the coordination and synchronization of all individual cells of an undulator system for FEL operation. This movement needs to be dynamic in order to avoid long adjustment times. In addition, the global control system has unrestricted access to all components of all cells. It controls and synchronizes the movement of individual cells as requested for the operation of the whole undulator system.
2. It provides status and error information of the whole system.

3 It provides the interfaces to the distributed object-oriented control system (DOOCS) of the linear accelerator and allows for full access to the hardware.

4 It provides an interface for user experiments. This includes the option to synchronize gap motion of the whole system with external device of a user experiment, such as a monochromator, for fast scanning of the radiation wavelength with “beam ON”.

5 It manages slow control tasks, such as temperature monitoring, remote rebooting, and handling messages of the fire-fighting systems

6 It provides a user interface and control console, visualization, etc.

7 It provides data storage, retrieval, and backup of the configuration and its parameters.

8 It provides flexibility for extension and modifications of the hardware such as the “seeding option”.

In addition, the global control system provides unrestricted access to the hardware of the undulator system, and can therefore be operated in many ways. Four examples are sketched in Figures 4–7. They correspond to Point 1 above.

Figure 4: *Parallel gap motion. All cells with all correctors and phase shifters are properly synchronized to the same gap.*

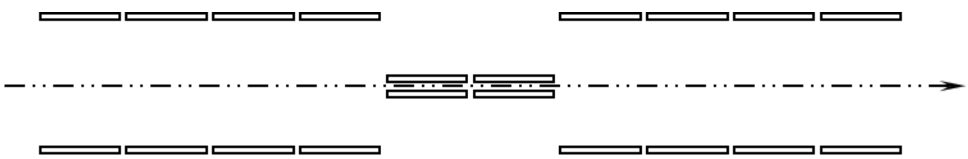

Figure 5: *Partial parallel gap motion: Same as Figure 4, but a part of the system is not used, by keeping the gap opened wide. In this way, the length of the undulator system can be reduced, for example, for long radiation wavelengths. In addition, if not all cells are used, the position of the source point can be varied.*

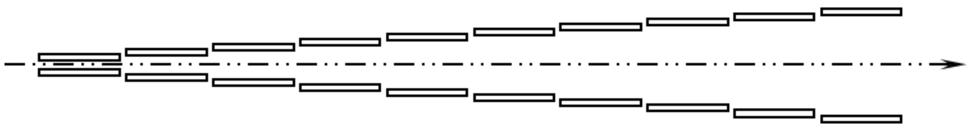

Figure 6: *Tapered operation: There is no continuous taper, a step taper is sufficient. Taper profiles, which optimize the radiation power, will be found empirically. The taper profile changes dynamically with the gap.*

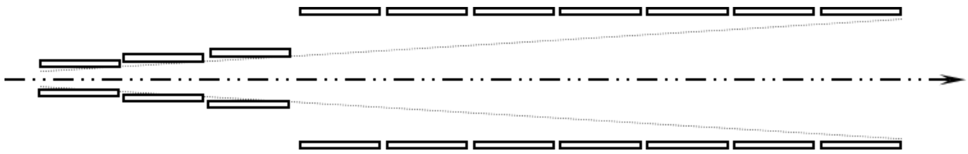

Figure 7: *Partial tapered operation in complete analogy to Figure 5*

In addition, numerous modes can be realized, which make use of the unrestricted access. The following list gives some examples related to photon diagnostics [3, 4]:

- In order to exactly measure the radiation wavelength of an undulator segment, its spontaneous spectrum is measured with the *K*-monochromator as a function of gap.
- The lookup tables for the air coil correctors may be re-checked or updated to maintain precise compensation for gap-dependent errors of the undulator.
- The phase shifter lookup tables may be re-checked by using two individual segments and controlling the phase shifter in between in a special way.
- The air coil correctors may be used for electron beam–based alignment (EBBA) to get a straight orbit within ±1 μm.

These are only some examples. More scenarios are possible.

3 Undulator control system design

The undulator control system is operated in the context shown in Figure 8. Users interact with the system through high-level commands that are translated into low-level control of each single undulator. Additional inputs, such as the state of the tunnel infrastructure or timing signals from the machine control, have an impact on system behaviour. System configuration is supported by a database.

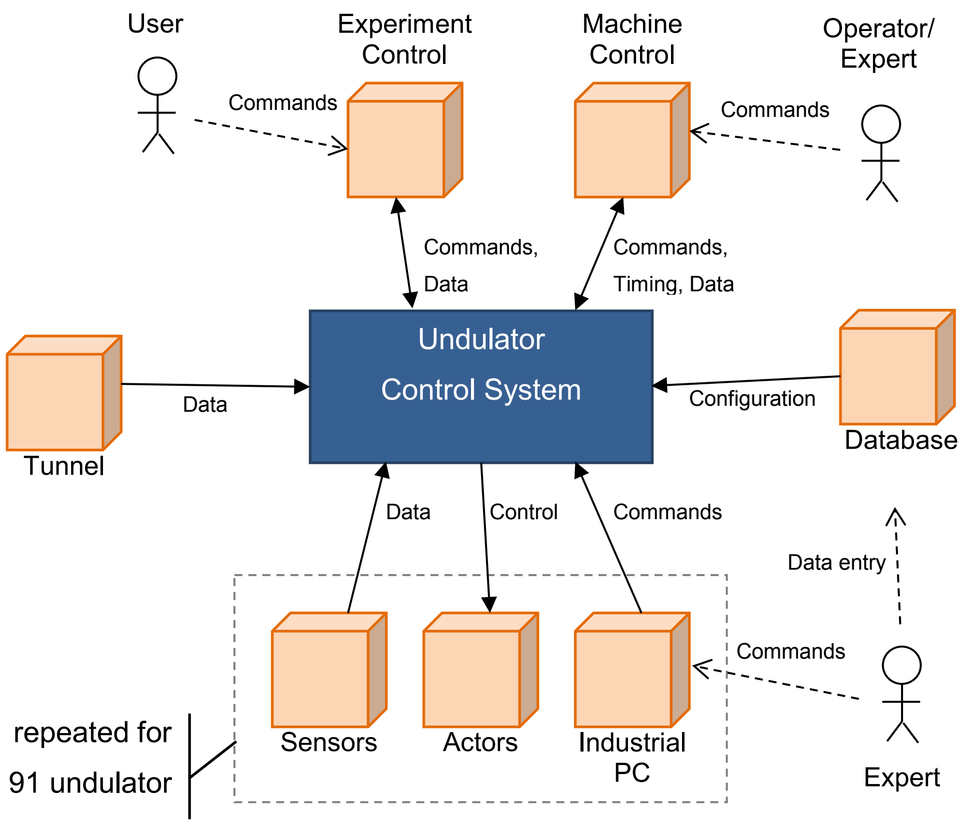

Figure 8: *System context*

The areal dimension of the undulators requires a distributed control system. On undulator cell level, there is a local control with a direct connection to sensors and actors. This control takes care of a precise movement of the girder motors to tune the undulator to the desired gap, and also to drive the phase shifter and magnetic-field correction coils as a function of the gap value.

On undulator system level, there is a global control with a real-time capable network connection to each of its' local controls. This control takes care of the synchronized tuning of one or more undulator cells to the desired gap. The global control also provides an interface to the users. It integrates seamlessly into DOOCS, which is the standard machine control system of the European XFEL accelerator [2].

3.1 Components

The undulator control system, as shown in Figure 9 and 12, consists of the following components:

- ***Central control node (CCN)***: receives motion commands from machine control and translates them into individual commands for each local control node (LCN). It also collects status data from each LCN and provides it back to machine control.
- ***DOOCS server***: interfaces between DOOCS clients on the machine control network and CCN. Both experiment users and machine operators use DOOCS clients to control the undulators through the DOOCS server.
- ***EtherCAT field bus***: used for real-time communication between CCN and LCN
- ***Undulator network***: used for remote access to LCNs and exchange of data that does not have real-time requirements.
- ***LCNs***: a programmable logic controller (PLC) that runs on industrial PC and controls all front-end devices belonging to one undulator cell. These include:
  - *Motors*: four servo motors per undulator, one stepper motor per phase shifter, and two stepper motors per quadrupole mover
  - *Beam trajectory correctors*: by means of air coil correctors

— *Three-way valve controller:* used for thermo-stabilization of the vacuum chamber

— *Feedback system*: based on absolute linear encoders, absolute multi-turn rotary encoders, LVDT position sensors, and a temperature measurement system

- ***Database***: contains configuration data for the undulator systems

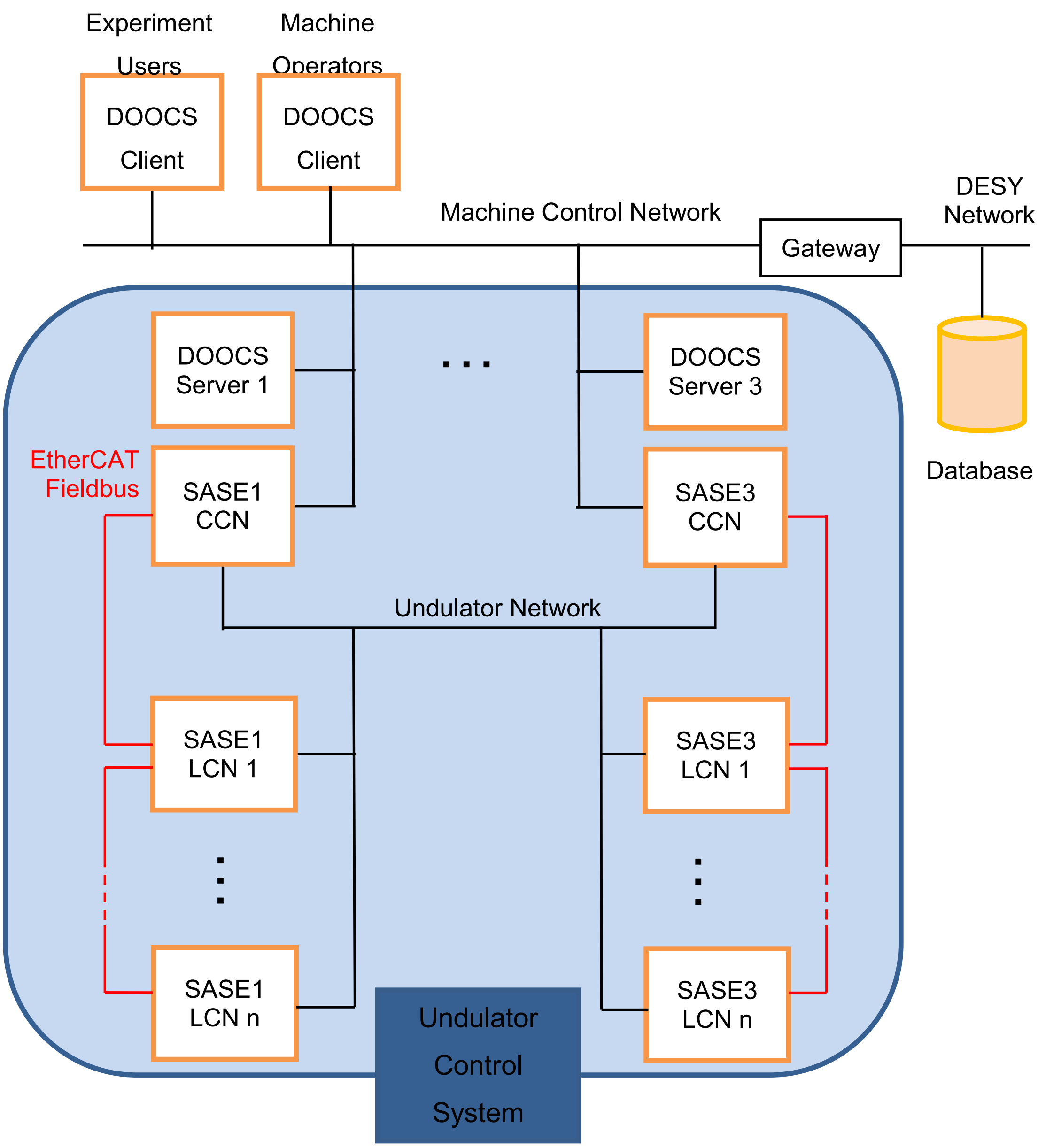

Figure 9: *Undulator control system components*

Each undulator system (SASE1, SASE2, and SASE3) has its own DOOCS server, CCN, and EtherCAT field bus. In case of failures of one of these components, only one undulator system is affected. The undulator network is shared between all undulator systems.

3.2 Network implementation

The CCNs will be installed in the balcony computer service rooms, which are located above the tunnel entry in the experiment hall (XHEXP1). One CCN will serve one undulator system. The CCN is connected to its undulator system through the nearest tunnel by means of optical fibres. The undulator cells are daisy-chained by copper cables (Figure 10.).

For the undulator system, a “redundant ring topology” will be used. This type of topology can tolerate a single point failure. Each SASE string will have two redundant rings, one for Ethernet and one for EtherCAT.

The EtherCAT network is used for real-time device and motion control, while the Ethernet is used for monitoring and remote access to the individual undulator PCs.

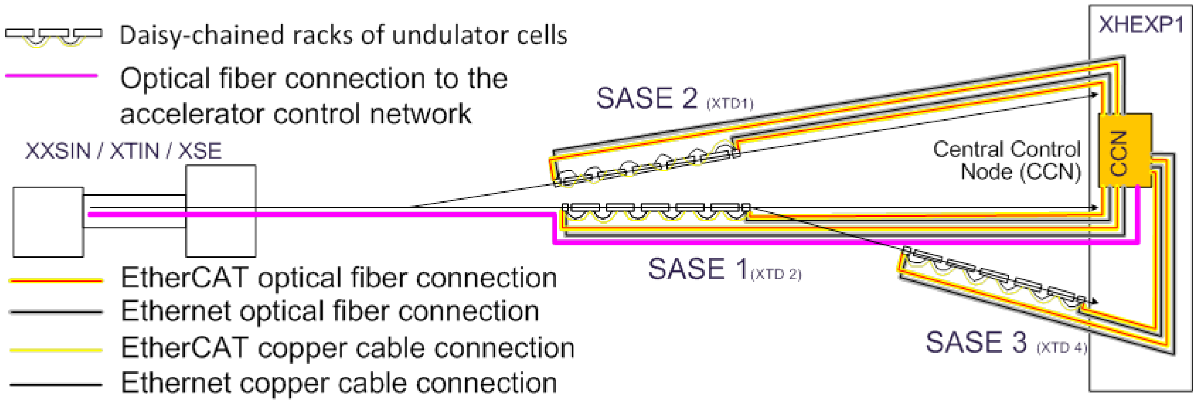

Figure 10: *Layout of the network topology*

The CCN will also have a dedicated optical fibre connection to the accelerator control system, which will be located in the injector building. The layout of one undulator control system is shown in Figure 11.

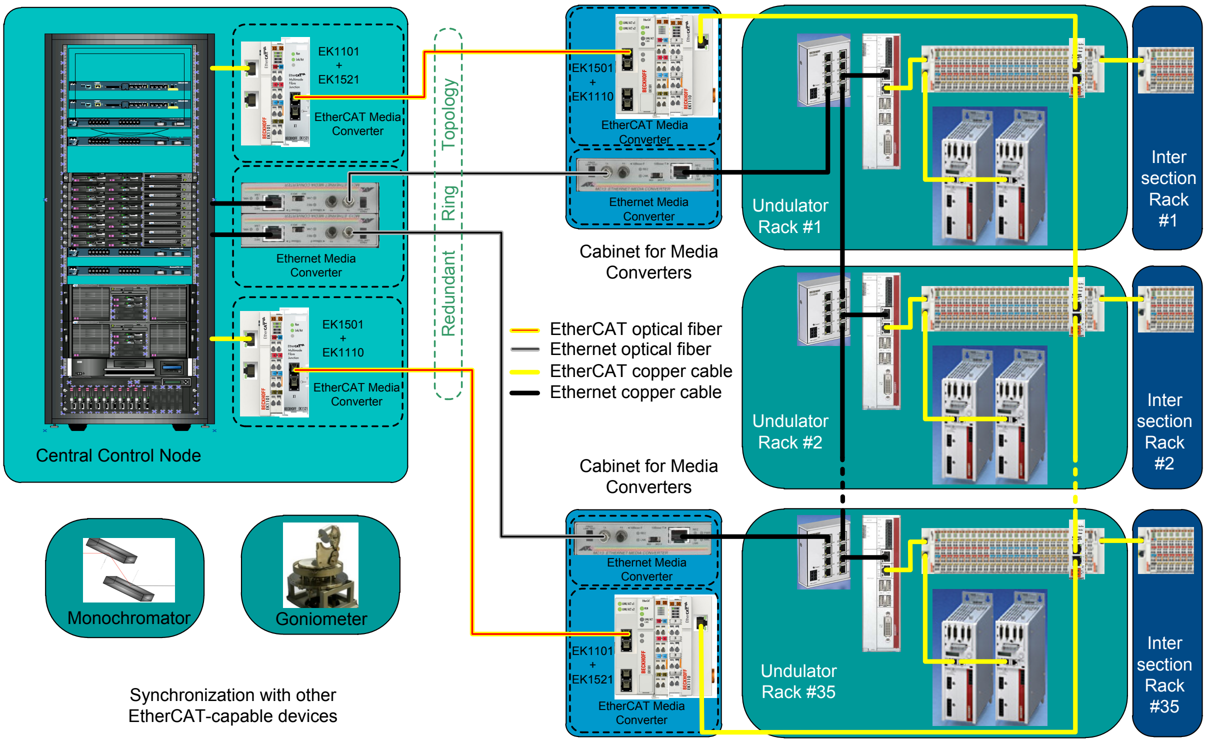

Figure 11: *Layout of one undulator control system*

3.3 Control parameters for undulator system

It is foreseen that user experiments will have selected control over the following parameters of the undulator system:

- *K*-parameter through undulator gap implemented as $K_{(gap)}$ table
- *K*-parameter taper (to optimize photon beam intensity)
- Synchronization with external devices

In contrast, the accelerator control will have full access over all undulator system parameters.

4 Global control of undulator systems

The main task for the global control is a synchronized gap change of the undulator cells. The simplest way to achieve this is to use a distributed clock (DC) feature of the EtherCAT field bus, which allows defining a common time base for the CCN and LCNs, with an uncertainty of less than 100 ns. With this feature enabled, the starting time for gap changes can be precisely synchronized (<< 1 µs) between undulator cells [6]. After starting a gap change, the cells are running freely but at constant speed, which means that there might be slight differences between cells during the change on the order of 2–5 µm.

A more advanced technique uses a virtual master axis in the CCN. The LCNs couple their physical axes to this virtual master axis to precisely follow its movement. Inside the LCN, all axes and parameters depending on the magnetic field strength, i.e. on the undulator gap, are coupled to this one virtual axis (Figure 12). Four undulator axes, one phase shifter axis, and four air coil correctors are the components that can be controlled locally and coupled to the virtual axis. Nevertheless, the LCN also contains components, like a quadrupole mover, an ambient magnetic-field correction coil, or a three-way valve, which are not directly depending on the undulator gap. These components are thus not coupled to the virtual axis [7].

The global control also performs slow control tasks, like temperature monitoring in the racks, remote restarting of undulator PCs by means of a neighbouring PC, or handling the messages from the fire-fighting system.

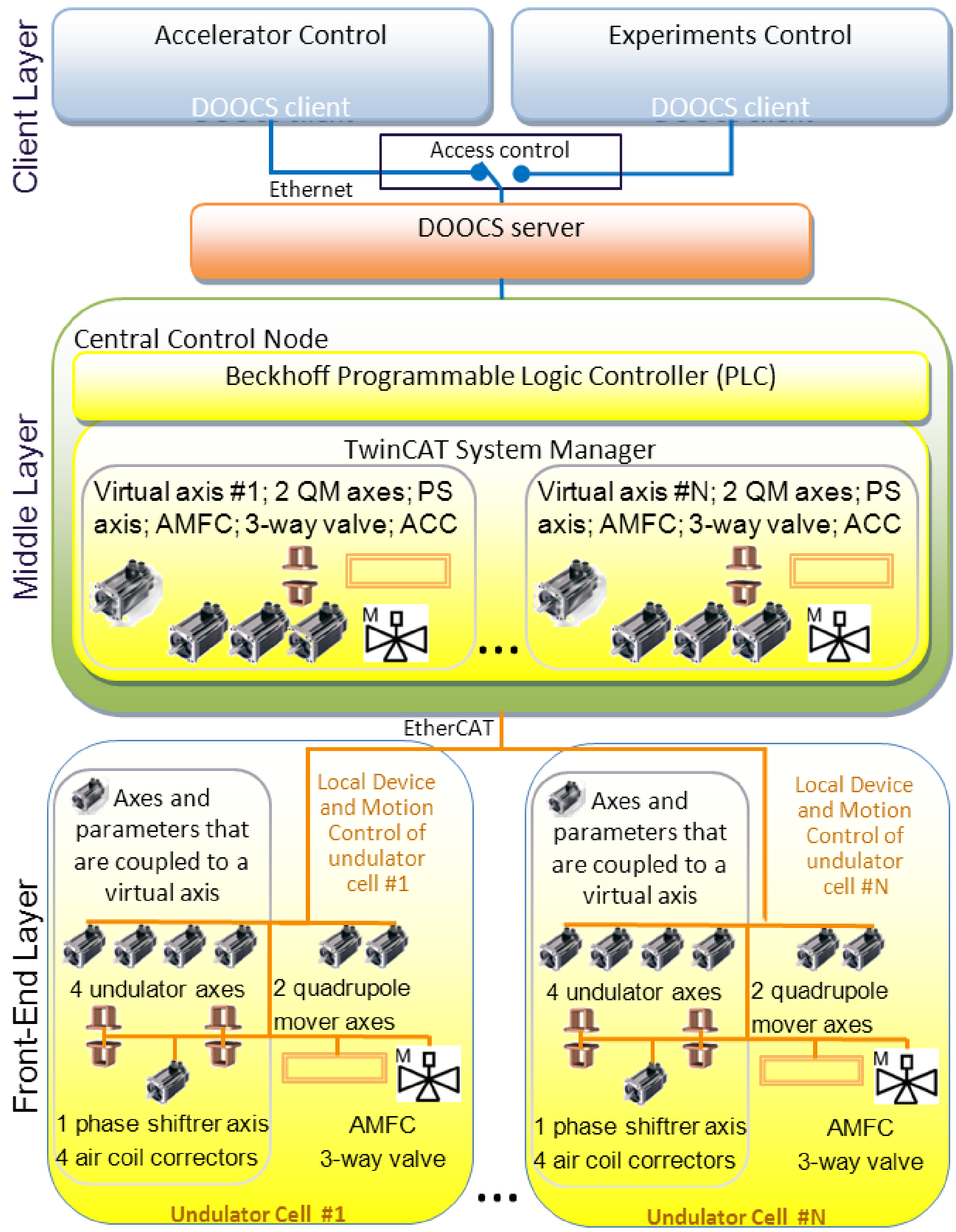

Figure 12: *Global control with virtual axes*

4.1 Interface to machine control

The global control consists of a Beckhoff TwinCAT PLC running on the CCN. Remote access to the PLC is possible with the Beckhoff automation device specification (ADS) protocol, however only from Windows platforms. Therefore an additional device server is installed on the CCN, which provides a ZeroMQ message interface on the network side and an ADS interface on the PLC side. ZeroMQ is available as open source for both Linux and Windows platforms [8]. A DOOCS server integrates the undulator system into the machine control network and runs on a separate Linux host. It can be a different computer or a virtual machine inside the CCN[1]. The DOOCS server exchanges data with the PLC through the message interface of the device server, which translates between ZeroMQ messages and ADS method calls. Figure 13 illustrates the integration of the PLC-based global undulator control into the DOOCS machine control system.

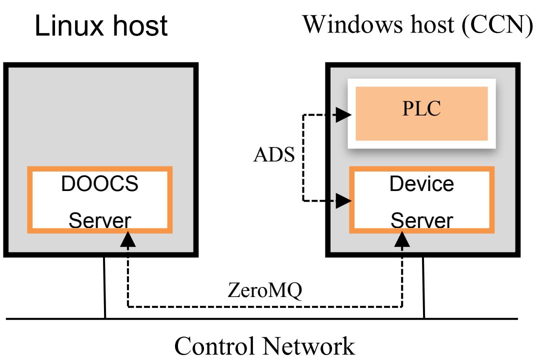

Figure 13: *Integration of undulator control into DOOCS*

Data is exchanged between the DOOCS server and the PLC using two schemes:

- Exchange on request, or alternatively
- Exchange on value change

Exchange on request is used to set data in the PLC or to get data from the PLC. It is initiated by the DOOCS server, and data values are exchanged in both directions. Exchange on value change is initiated by the PLC, and data values are exchanged only in the direction from PLC to DOOCS server. It is used for data that require online monitoring by machine control, so that the values are available in the DOOCS server for immediate retrieval.

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[1] DOOCS server software is only available for Linux platforms. It has been decided to run the DOOCS server on a Linux host, instead of porting DOOCS software to Windows.

Access control to the DOOCS server is based on Linux user and group IDs. The DOOCS server can be configured to accept write access to any of its properties only for DOOCS clients that run with a specific user or group ID. Read access is not protected and is always allowed for any client. Arbitration between write accesses of the two DOOCS clients for the experiment user and machine operator needs to be handled outside of the undulator control system. The undulator control system only provisions against damages to the undulator system due to contradictory write data.

4.2 Control of undulator system *K*-parameter

The global control supports *K*-parameter control of the undulator system according to the pattern described in Section 2.3. The operator may set either a single *K*-parameter value for a parallel operation, or a minimum and maximum *K*-parameter value for a step taper operation. It is possible to mask individual undulators so that they are taken out of operation by opening wide. In addition, it is always possible to set the *K*-parameter for each undulator individually to allow any user-defined pattern.

Inside the CCN, the *K*-parameter is translated into a corresponding gap value for each undulator using lookup tables. The lookup tables are generated individually for each undulator during a calibration run of the undulator system.

Once the *K*-parameter is set, the operator needs to issue a start command to initiate the gap change of the undulators. The gap change may be synchronized with signals from the timing system.

5 Local control of undulator cell

An undulator cell consists of a 5 m long undulator segment and a 1.1 m long intersection segment (Figure 14). Four servo motors are used on each undulator to control the gap between girders with micrometre 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 the magnetic-field correction coils and the gap of the phase shifter are adjustable as a function of the undulator gap [9, 10].

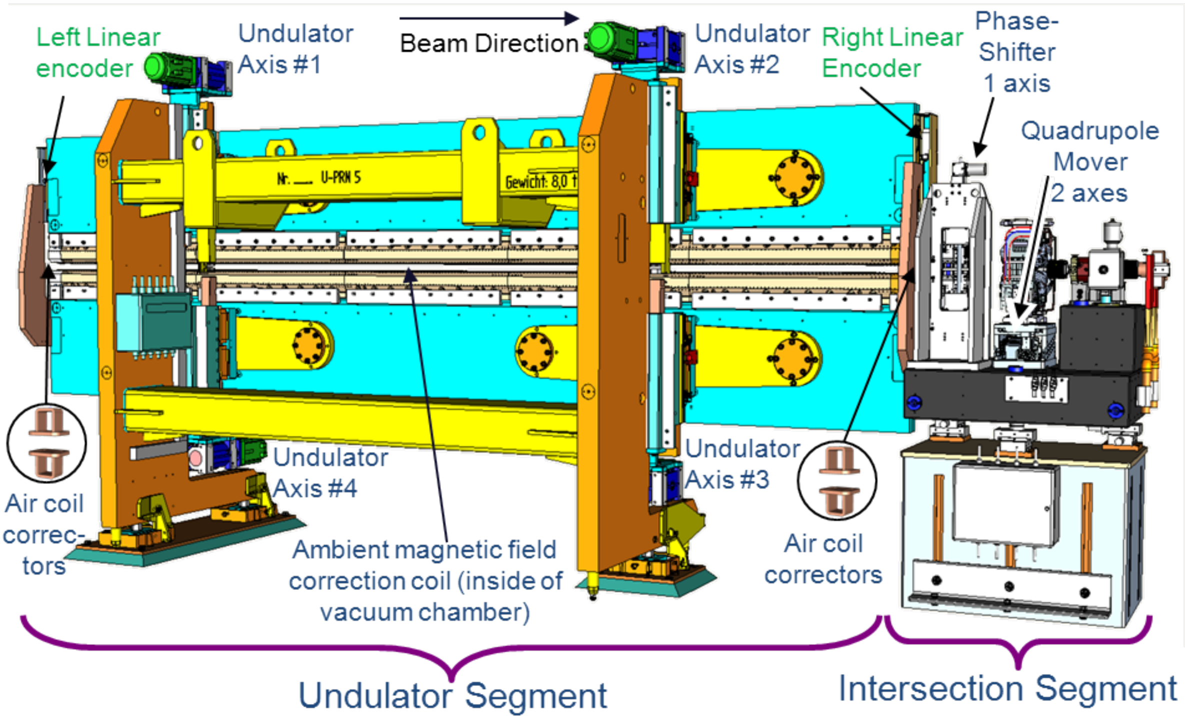

Figure 14: *Undulator cell. Undulator and intersection segments in array.*

5.1 Control of the undulator gap

Each of the four undulator motors is equipped with a rotary multi-turn 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 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 (Figure 15) that are implemented as feed-forward corrections farther in the PLC program.

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

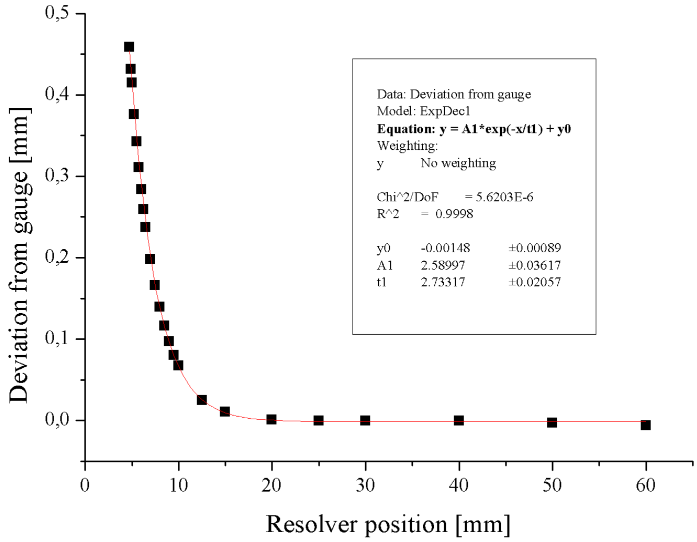

Figure 15: *Evaluation of the correction curves for one axis*

In case the linear encoders are used 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.

5.2 Temperature change 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. This 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 [11]. The required gap correction is calculated in the PLC program. The correction is done according to Equation 1:

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

where $\Delta T_{Loc} = T_{Nom} - T_{Loc}$, 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}), and b and c are empirical constants describing the gap dependence of the peak field.

At 10 mm gap, for instance, the temperature dependence for SASE1 and SASE2 is ~9.17 µm/K, for SASE 3 this dependence is ~15.7 µm/K.

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 [12].

5.3 Temperature control of the vacuum chamber

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 a three-way valve. The actual water temperature of the three-way valve outflow is measured by a PT100-3 sensor, which is connected to the Almemo 8590-9 temperature measuring device and provides feedback to the PLC program. In the PLC program, the water temperature and the temperature of the magnetic structure are compared, and the three-way valve is controlled to eliminate any deviation.

5.4 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),
- 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 lookup tables. These lookup tables contain the steering strengths as a function of undulator gap that are required to compensate the first and second field integral errors. These steering strengths are derived from magnetic measurements. The required correction currents are calculated from the conversion constants, which are in the range of 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. The device is called “two wire corrector” (TWC) [13]. It can be used for compensation of an ambient magnetic field of up to 150 μT.

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

5.5 Phase shifter control

For gap-adjustable undulator systems, phase shifters are needed to adjust the phase between microbunched electrons and the photon field. A phase shifter for the European XFEL is based on permanent-magnet technology. The magnet structure consists of four magnetic arrays, two at the top and two at the bottom. The phase is adjusted by changing the gap between upper and lower magnetic arrays [14].

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 (Figure 16).

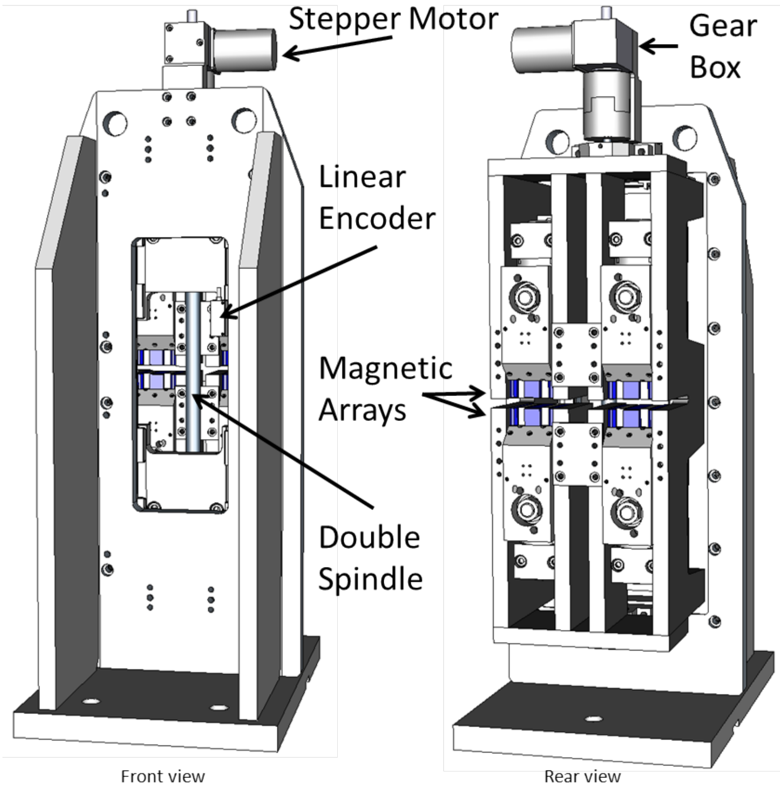

Figure 16: *Motion control components of the phase shifter*

The phase shifter is controlled by means of a lookup table, which is evaluated from magnetic measurements. Both motion controls, of the undulator and the phase shifter, are synchronized with a following error of ≤10 μm. Figure 17 shows the dependence of the phase shifter gap value as a function of undulator gap value for SASE1/2 and SASE3 at different harmonic numbers [15]. The basic control requirement is that the phase shifter gap has to follow the undulator gap.

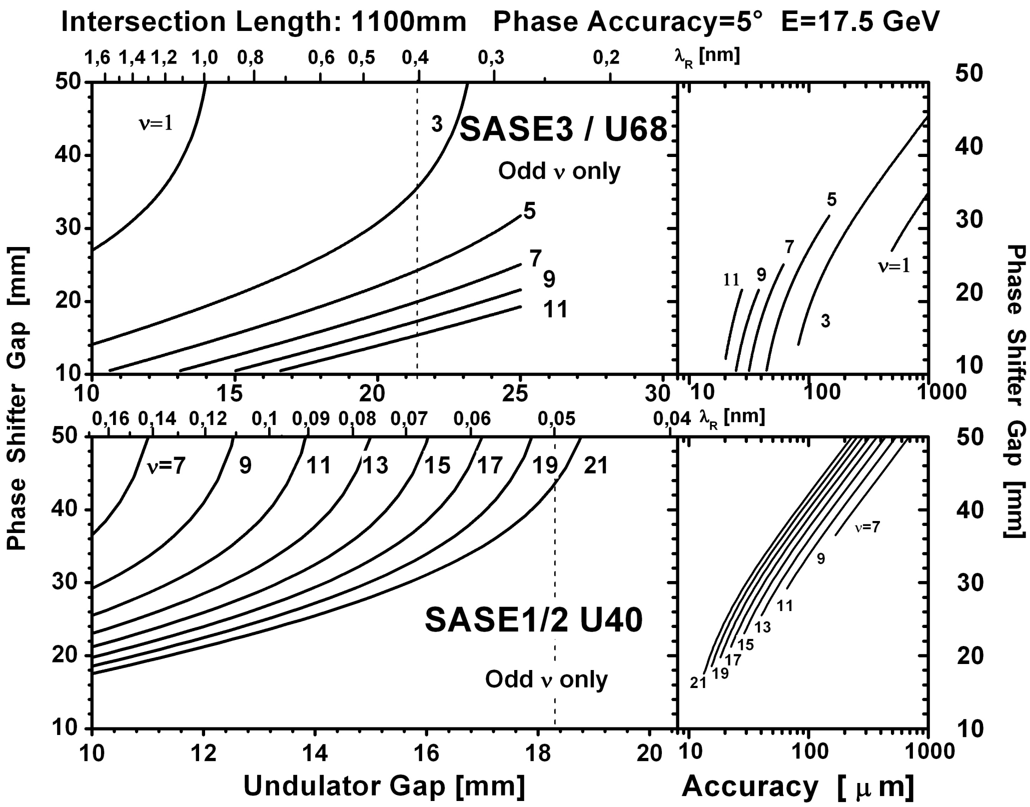

Figure 17: Tuning curves for the phase shifter. The graphs on the right show the gap precision of the phase shifter required to control the phase within ±10°.

5.6 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. The undulator local control receives this information from the accelerator control via the global undulator control system. The requirements for the quadrupole mover control are the following:

- Movement range in horizontal and vertical directions: ±1.5 mm.

- Positioning repeatability in both directions: ±1 µm.
- Maximal movement speed in both directions: 1 mm/s
- Maximum load: 75 kg

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.

5.7 Remote and local operation

The local control system of each undulator cell is completely implemented in Beckhoff's PLC and the TwinCAT system manager. It allows control of the undulator cell either locally, using local graphical user interface (GUI), or remotely by means of TwinCAT ADS communication library. The TwinCAT interface for programming languages like C/C++ or Java offers links to I/O data as well as full access to the methods of the PLC/NC run time server (start, stop, etc.). ADS data exchange can be managed over different physical transport routes, like TCP, UDP or EtherCAT.

The local GUI consists of the following windows:

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

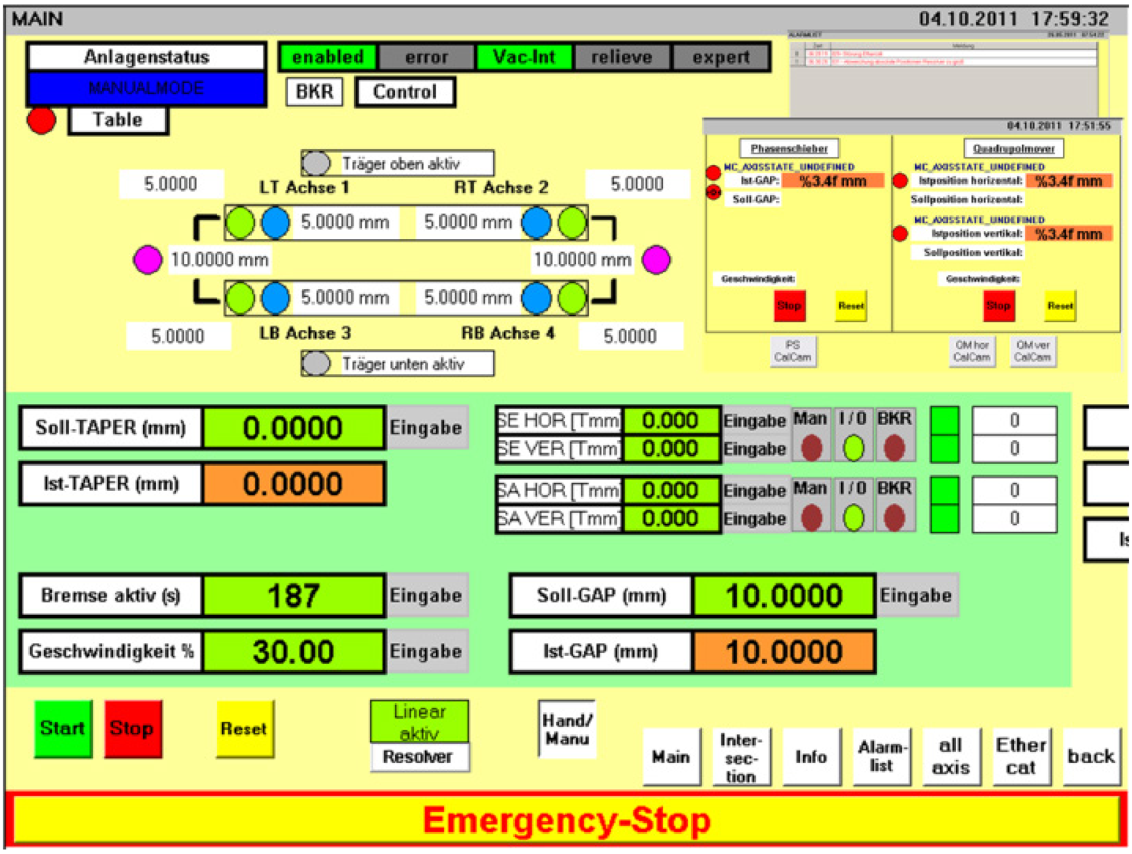

Figure 18: *GUI windows of the local control for the undulator cell*

The local control system provides all possibilities for control, monitoring, 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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