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INSTALLATION AND HARDWARE COMMISSIONING OF THE EUROPEAN XFEL UNDULATOR SYSTEMS

M. Yakopov†, S. Abeghyan, S. Karabekyan, J. Pflueger, European XFEL, Schenefeld, Germany

Abstract

This article describes in detail the steps of hardware installation and commissioning of components for undulator systems at European XFEL. In general, the work can be divided into 3 different steps: installation, alignment, and commissioning. During installation step, the following main components were rolled into the tunnel: - undulators with the control cabinets, intersection control cabinets, phase shifters, quadrupole movers, correction coils. They have been mounted according to the designed positions. Then all mentioned components have been aligned according to the specifications. Finally, the cabling has been done and basic tests were performed. As part of the commissioning, the calibration of the temperature sensors, as well as the measurements of the quadrupole mover travel distance has been done in the tunnel. Afterwards, the undulator limit switches and hard stops were adjusted to secure the vacuum chamber by closing the undulator gap up to 10mm. Eventually, the system was handed over to the global control system in order to perform all functional tests. The main focus is given to the components which are controlled or monitored by the undulator local control system [1].

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) will be operated by using tree undulator systems based in total on 91 variable gap undulators. The SASE1 system is commissioned, it is in operation and delivering the photon beam to the experimental hall with the following parameters: 300muJ, 9.3keV up to 30 bunches, for the FXE (Femtosecond X-Ray Experiments) and the SPB/SFX (Single Particles, Clusters, and Biomolecules and Serial Femtosecond Crystallography) instruments. The first lasing has been achieved in May 2017. The SASE3 undulator system is commissioned and ready for the operation which will start in October 2017. The last SASE2 system is currently installed in the tunnel and will be commissioned by the end of the year 2017. All three systems are designed in the same fashion, and installation sequence of actions is identical for all three undulator systems: SASE1 (Self-Amplified Spontaneous Emission), SASE2 and SASE3. The description of SASE1 system is presented.

INSTALLATION ACTIVITIES

Before being installed in the tunnel all hardware components have been commissioned and validated in the laboratory by performing the number of tests. The SASE1 undulator system contains of 37 sections, so called cells. Each typical cell includes an undulator and an intersection. Only first two cells are not equipped with the undulators. This scheme has been realized for the future evolution of the SASE system by implementing the self-seeding feature. Each intersection is including a number of hardware components: vacuum chamber absorber, beam position monitor, beam loss monitor, quadrupole lens installed on the quadrupole mover and phase shifter. The phase shifter and quadrupole mover are part of the undulator local control system.

After equipping the tunnel with all necessary basic infrastructure such as light, power lines, water supply pipes, main air flow system and reaching the acceptable temperature and humidity conditions, undulator control racks (UCR), intersection control racks (ICR), intersection control nodes (ICN), and media convertor racks (MCR) have been installed. All mentioned racks are the parts of the undulator control system, which is based on the real time Beckhoff automation technology. The PLC program is implemented in the TwinCAT system [2] and running on the Industrial PC (IPC's) installed in the UCR's. The undulator cell is shown in Figure 1.

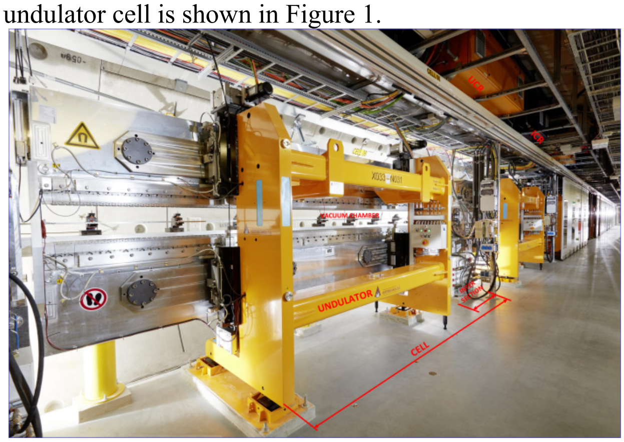

Figure 1: The view of SASE1 cell, equipped with the undulator system components: vacuum chamber, undulator, intersection, UCR and ICR.

As a part of the water supply system the 3-way valves which are modulating control valves with magnetic actuators (Siemens MXG461B) have been installed on each cell, for the vacuum chamber temperature stabilization system.

Vacuum Chamber Temperature Stabilization System and Two Wire Correction System

The temperature of the vacuum chamber in the undulator gap needs to be identical to the temperature of the magnetic structure to avoid the girder deformation due to the transverse heat flux, which occurs if the vacuum chamber is at a different temperature than the magnet girder. This is done with a vacuum chamber water cooling system. For efficient operation of the water cooling sys-

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tem, cooling water temperature is stabilized within the accuracy ±0.1°C.

For temperature stabilization of vacuum chamber a concept of automatic permanent mixing of hot (26°C) and cold (16°C) water with a 3-way valve has been adopted. The cooling water is circulated by two 4mm diameter holes extending along each 6,1m long vacuum chamber segment, from both sides of the beam line hole. Temperature-stabilized water, named in the control system as “Actual Mix Temperature”, is connected to the vacuum chamber in parallel. In this case the temperature gradient across the vacuum chamber is minimal, but there is a gradient along the vacuum chamber. To minimize the temperature gradient the feedback temperature sensor has been installed in the middle of the vacuum chamber segment. To compensate the influence of the ambient magnetic field on the electron beam along the undulator segments, the two wire correction system (TWCS) has been designed. The TWCS is based on a long parallel coil with two turns, which surrounds the electron beam. By controlling the current in the coil, an adjustable magnetic field of up to about ±500µT can be produced to compensate the vertical component of the ambient magnetic field in the undulator. The excitation current is generated by a power supply controlled by the local undulator control system. The schematic view of the vacuum chamber segment is presented in Figure 2. The vacuum chamber segments have been equipped with the TWCS coils before installation in the tunnel.

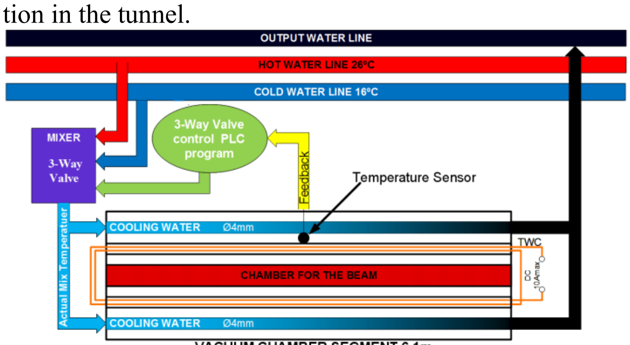

Figure 2: Schematic view of the parallel water connection scheme and the control system of the mixer. Two wire connection system (TWC).

The set temperature for the temperature stabilization system is calculated as an average value of three temperature sensors, which are measuring the undulator magnetic structure temperature along the undulator. The calculated value is used as a set value in the control algorithm. This procedure is included in the 10ms PLC cycle.

Two different types of water supply have been implemented in the undulator system. The stainless steel pipes are used for supplying the aluminium components like the vacuum chamber, copper pipes are used for supplying the components with the copper pipes, like air coils and quadrupoles. Aluminium and copper water temperature sensors and respective water flow switches have also been installed to complete the water supply task.

Installation of the Intersection Components of the Undulator System

As a next step the installation of the vacuum chamber has been done. The special designed holders are used to make precise vacuum chamber alignment possible. After vacuum chamber installation the quadrupole movers, quadrupole magnets and phase shifters have been placed on a pre-installed intersection granite stones.

Phase Shifter For gap adjustable undulator systems, phase shifters are needed to adjust the phase between electrons and photons field. The phase shifter is based on permanent magnet technology. The magnet structure consists of 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. The detailed explanation is given in ref. [1]. The basic control requirement is that the phase shifter gap has to follow the undulator gap, which has been implemented in the local control system via a look up table.

Quadrupole Mover The control of the quadrupole magnet mover is a part of the local undulator control system. 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. Figure 3 gives an overview of intersection cmponents.

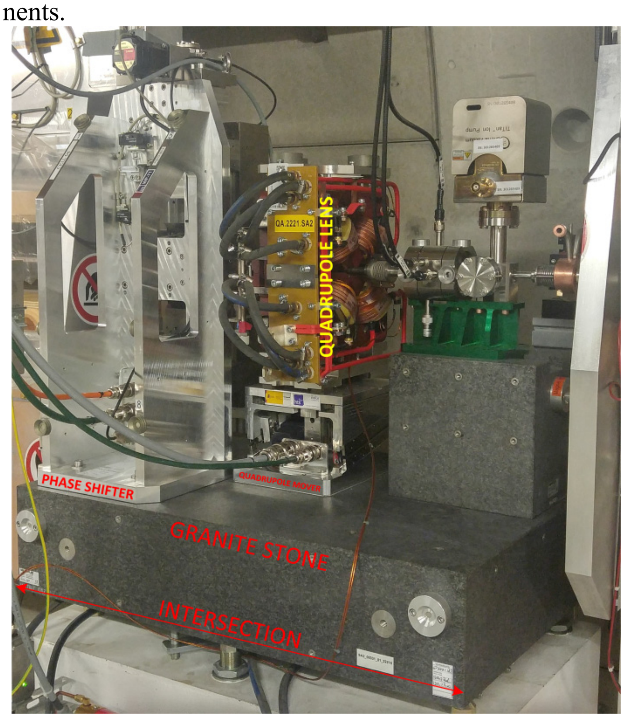

Figure 3: Intersection components installed on the granite stone in the tunnel and connected to the undulator control system.

During the installation of the described components, the preliminary alignment procedure has been done by alignment group, to bring the vacuum chamber together with the intersection components in the required nominal

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position. Once it was done, the undulators have been rolled into the tunnel, transported by the special vehicle and installed in the required positions one by one. The installation sequence of the undulators and phase shifters has been given in advance, based on the magnetic measurement results. The RadFET sensors have been installed on each undulator girder at the upstream side of the magnetic structure, in order to detect the radiation level during the operation of the undulator. The monitoring and data transfer of the measured values are realized online. Finally, the upstream and the downstream magnetic field corrector coils have been installed on both sides of the undulator.

COMMISSIONING OF THE UNDULATOR SYSTEM

Once the cabling has been done, the Ethernet and EtherCAT connections have been established between the central control node (CCN) [1] and the undulator cells through the media convertor racks. They are installed at the both ends of the SASE system to support the redundant ring topology.

Software Applications

A number of the Supervisory Control and Data Acquisition (SCADA) software have been developed and used during the commissioning phase:

- Undulator System Database [3] has been created to store the individual parameter for each hardware component. The database contains a different type of data, such as hardware serial numbers, offset values and software limits for the motion control applications, calculated and measured look up tables for all types of dependencies which are required during the operation of the undulator system.
- Image Deployment Automation (IDA) [4] is a software solution for the remote master image deployment on the C-Fast cards of the IPC's in a row over the Ethernet. The software provides a possibility to create the master image and deploy to IPCs. The master image includes the Microsoft Windows Embedded OS with the TwinCAT PLC runtime system and all required software packages and environments. During the master image deployment procedure, all individual parameters are copied from the database, and eventually, the automated configuration of each local undulator control system is proceeding. For example the correction values gained during the alignment procedure of the quadrupole lens have been filled in the database and subtracted from the existing offset values for the quadrupole mover axes. The newly calculated values have been distributed over the undulator system during the image deployment procedure and later on demand.
- SASE tester [3] is intended to use during the maintenance periods of each SASE system. The purpose of software is to test the hardware and software components of the undulator system. The tests are processed in parallel for each cell and can be selected individually. The tests are covering the following hardware components: undulators, phase shifters, quadrupole movers, air coil correctors, cabling, terminal operation statuses, temperature sensors, rack door statuses, and etc. Engineers can select the desired tests to be performed and also the number of times the test should run. The test results are displaed and if test failed, it shows the reason of the failure. The software can also export results in text file for using in documents. The design of the software ensures extensibility, so new tests can be added or existing tests can be modified. Typical test scenarios are described below. Before performing the tests, SASE tester is checking whether the system is in emergency mode and if necessary enabling control voltage. Additionally, it ensures that the phase shifters are homed.

Hardware Commissioning

NdFeB permanent magnet material is used for the undulator segments. It has a temperature coefficient of about 10^{-3}/°C. Therefore, temperature stability has a strong influence on the wavelength of the emitted photons. In order to compensate this temperature influence, a gap correction is applied by the undulator control system [1]. Three temperature sensors are installed on each undulator segment and one on each vacuum chamber section to measure the local temperature accurately. They are connected to the ALMEMO 8590-9 data acquisition system, which is also a part of the undulator local control system. The measured values are then transferred to the PLC program and visualized in the GUI. In order to provide an accurate data, the calibration of the temperature sensors, used for these measurements, has been done. A special setup has been developed for this particular task to make comparative measurements between the certified calibrated temperature sensor and the sensors which have to be calibrated. The calibration has been done in the temperature range from 16°C to 26°C with 1°C step. The calculated offsets and slops have been stored in the EEPROM memory of each temperature sensor connector. A special software has been developed to calibrate and monitor the sensors and also to store the calibration parameters automatically.

Adjustment of the Limit Switches and Hard Stops of the Undulator

In order to secure the save undulator gap movement up to required 10mm, respective limit switches and the hard stops have been adjusted. The main reason is to secure the vacuum chamber, which is placed in between the upper and lower undulator girders. For this reason the software limitation of 10mm gap is implemented in the local control system, as well as two separate levels of limit switches. The first level limit switches have been adjusted to be activated at the gap 9.95mm ±25µm. This value can be reached due to the inertial movement of the undulator girders, and magnetic force which bends the undulator

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frame. The second level limit switches are intended to protect the vacuum chamber from being damaged by the magnetic structure end poles in case of the tapering of tilting the undulator girders with respect to the vacuum chamber. They are adjusted to be activated at the gap 9.8mm ±25μm.

To mechanically secure the vacuum chamber in case of inertial movement of the undulator magnetic girders, two hard stops are implemented in each undulator. The hard stopes are adjusted in the way to secure the vacuum chamber even in case of uncontrolled movement of the girders. The hard stops have been adjusted in the way to secure the 9.6 mm, high vacuum chamber in one hand, and allow to reach the 10 mm gap in the another. To be able to stop the motion of the girders by means of the hard stops and at the same time to secure the undulator from unnecessary shock, the limitation up to 30% of full range of the current of the undulator servo motors for closing gap direction has been implemented as a default setting in the System Manager. Since the main power is required to open the undulator gap, and at the same time it doesn't threaten to damage the vacuum chamber, the axis current in that direction is not limited. As a very last step the air coil magnetic field correctors have been installed and adjusted.

The Tests Performed by SASE Tester Software

After completing the adjustment procedure, the following tests were performed:

- Two groups of tests have been done with the undulators: stand-alone and coupled with the phase shifter. In stand-alone mode the undulators are changing the gap back and forth to the target positions. In coupled mode the undulator will be coupled first and move along with the phase shifters.
- The test with the phase shifters has a similarity with the undulators. It mainly consists of changing the gap between target positions. Additionally, the homing procedure has been tested.
- SASE tester provides target position testing for both, horizontal and vertical axes of quadrupole movers. This test has been done as well.
- The air coil correctors have tested by applying the magnetic field and checking the feedback value.

SASE tester is highly configurable from the user interface. Most of timings, error thresholds, target positions, temperature tolerances and delays are available in configurations for each device. An example of the tests configuration tab of the SESE tester software is presented in Figure 4.

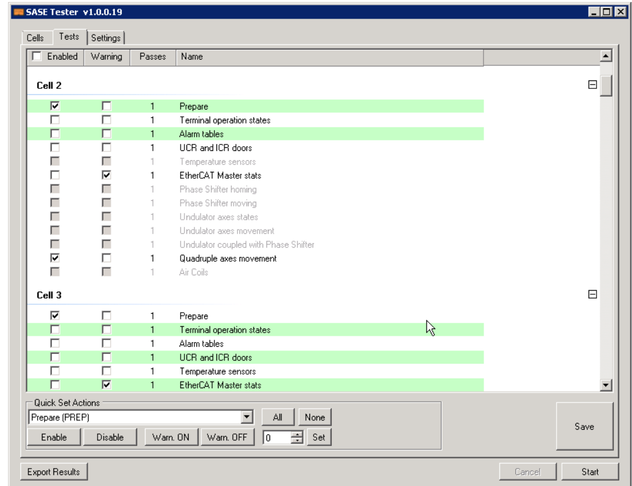

Figure 4: A view of the SASE tester configuration tab.

CONCLUSION

A big number of different DESY support teams and external companies have been heavily involved in the installation and alignment phases. The experience gained during the development of the SASE1 undulator system has been beneficially used during the same activities in SASE2 and SASE3 undulator systems.

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