ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOMS052

CONSIDERATONS FROM DEPLOYING, COMMISSIONING, AND MAINTAINING THE CONTROL SYSTEM FOR LCLS-II UNDULATORS*

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Abstract

Two new undulator lines have been installed as part of the Linac Coherent Light Source upgrade (LCLS-II) at SLAC National Accelerator Laboratory. One undulator line, composed of 21 horizontally polarizing undulator segments, is dedicated to producing Soft X-Rays (SXR). The other line, composed of 32 vertically polarizing undulator segments, is dedicated to producing Hard X-Rays (HXR). The devices were installed, and the control system was deployed in 2019. Commissioning culminated with the achievement of first light from the HXR undulator in the Summer of 2020 and from the SXR undulator in the Fall of 2020. Since then, both undulator lines have been successfully providing x-rays to user experiments with very limited downtime. In this paper, we first describe the strategies utilized to simplify the deployment, commissioning, and maintenance of the control system. Such strategies include scripts for automated components calibration and monitoring, a modular software structure, and debugging manuals for accelerator operators. Then, we discuss lessons learned which could be applicable to similar projects in the future.

INTRODUCTION

Two new undulator lines have been installed as part of the Linac Coherent Light Source upgrade (LCLS-II) at SLAC National Accelerator Laboratory. One undulator line, composed of 21 horizontally polarizing undulator segments, is dedicated to producing Soft X-Rays (SXR). The other line, composed of 32 vertically polarizing undulator segments, is dedicated to producing Hard X-Rays (HXR). Details of the motion control system design and implementation are discussed in [1] and [2] and a brief overview is provided in the next section. Devices installation, deployment of the control system, and functional checkout commenced in the Summer of 2019 and was completed in the Spring of 2020. Commissioning culminated with the achievement of first light from the HXR undulator in the Summer of 2020 and from the SXR undulator in the Fall of 2020. Since then, both undulator lines have been successfully providing x-rays to user experiments with very limited downtime. In this paper, we focus on the undulators motion control and first describe the strategies utilized to simplify the deployment, commissioning, and maintenance of the control system. Then, we discuss lessons learned which could be applicable to similar projects in the future.

UNDULATOR LINE ARCHITECTURE

The LCLS-II undulator lines are organized in a repetition of identical segments called cells. Each cell being composed of an undulator segment and of an interspace break. The interspace supports a quadrupole magnet, vacuum components, beam diagnostic components and a phase shifter. An SXR undulator cell is shown in Fig. 1 with the main functional components numbered. The undulator segment (1) is positioned upstream of the interspace pedestal and plate (2). The BPM, quadrupole magnet, and vacuum components (3) are mounted on the interspace plate together with a phase shifter (4).

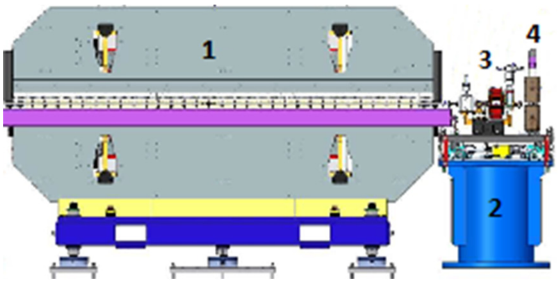

Figure 1: SXR undulator cell with main functional components numbered.

An HXR undulator cell is shown in Fig. 2 with the main functional components numbered. The undulator segment (1) is mounted on the same girder as the downstream interspace plate (2). This plate supports a quadrupole magnet, a BPM, a phase shifter, and vacuum components (3).

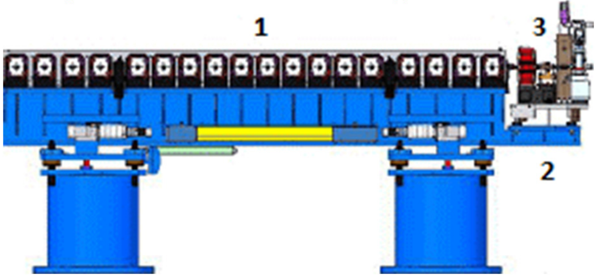

Figure 2: HXR undulator cell with main functional components numbered.

For each cell, the undulator motion control system provides users with the ability to set and read back the undulator segment gap and K value, and the relative position of the segment magnetic axis with respect to beam path. It also allows to change the pointing of the undulator line through a system of cam movers [3]. The phase shifter motion control system allows to monitor and set the phase

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shifter gap and phase integral. A temperature monitoring system allows to measure the temperature of the undulator segment and phase shifter magnets. The information is then used to scale the calculation of the K and phase integral value based on the devices gap.

Soft X-Ray Undulators (SXU) Motion Control Architecture

The gap of each SXR undulator segment is actuated by four servomotors with brakes coupled with a zero-backlash drive system. The actuators on the upper strongback utilize on-axis BiSS-C (33 bit) rotary absolute encoders for position and velocity feedback. Linear absolute BiSS-C (26 bit) encoders are used to measure the gap at the upstream and downstream end of the device. The two motors on the lower strongback utilize these encoders for position feedback. A custom Aerotech chassis containing four Ensemble CP10 drives allows coordinated control of the four undulator actuators. The vacuum chamber of each undulator segment is supported by the upstream and downstream interspaces and, together with the rest of the interspace components, can be positioned with five Degrees-Of-Freedom (DOF) through a cam system. This system is actuated by five stepper motors, one for each cam, receiving position feedback from rotary potentiometers. Two linear potentiometers, one at each end of the undulator segment, are used in conjunction with Aerotech autofocus functionality to maintain the undulator magnetic axis aligned with the beam path as the undulator line is repointed [1]. The gap of each SXR phase shifter is actuated through a servomotor with brake. A linear absolute BiSS-C (32 bit) encoder is used to measure the phase shifter gap and to provide feedback information to the gap motor. A custom Aerotech chassis containing five MP10 and one CP10 Ensemble drives is used to control the motion of the interspace cam movers and of the phase shifter. A Beckhoff system composed of a communication module and five RTD modules is mounted on the undulator frame and is used to monitor ten RTDs for each cell. The RTDs measure the temperature of the undulator and phase shifter magnets and of other components. The temperature readback is used to scale the undulator K and phase shifter phase integral calculations. Each Aerotech motor controller and Beckhoff controller is connected to the accelerator control network and accessed through an EPICS soft IOC as described in [1].

Hard X-Ray Undulators (HXU) Motion Control Architecture

The gap of each HXR undulator segment is actuated through four Animatics SmartMotors with integrated brakes and incremental encoders coupled with a gear system. SSI and BiSS-C (26 bit) absolute linear encoders are used for closed loop gap control at the EPICS level. Coordinated motion between the four SmartMotors is achieved through a CAN network. An equivalent approach is used to control the gap of the HXR phase shifter. A single SmartMotor with integrated brake and incremental encoder is used to actuate the device. A linear SSI absolute encoder measures the phase shifter gap and is used for close loop gap control at the EPICS level. Each segment girder, supporting the undulator and the downstream interspace components, can be positioned in space with five DOF through a cam system [3]. Each cam is actuated by a SmartMotor receiving position feedback at the EPICS layer from a calibrated rotary potentiometer. Motion control and interfacing with the accelerator distributed control system is implemented through a crate with an MVME3100 single board computer running an EPICS IOC on RTEMS. The crate communicates with the hardware through Industry Pack (IP) cards on Acromag AVME-9760 carriers. The VME-based IOC controls the motion of the HXR undulator, cam movers, and phase shifter. An analogue to digital VME IP card is used to interface with ten RTDs mounted in various locations along the girder. As for the SXR line, the RTDs are used to scale the undulator K and phase shifter phase integral calculations.

Undulator Line Control System

The control system for the undulator line was designed to have a modular and repetitive structure based around the undulator cell. This approach was adopted both at the local motor controller level and at the EPICS level. Coordinated control of each undulator line is then achieved through a set of Matlab scripts. This approach allows to operate each undulator cell independently from the neighbouring ones and simplifies deployment and maintenance. For example, it allows to swap undulators or perform maintenance on a cell without affecting the neighbouring ones. As discussed in the previous sections, at the motor controller level this is achieved through a dedicated controller for each device. At the EPICS layer, this is achieved by avoiding hard-coding device-specific information in substitution files and by having separate executables for each functional component. For example, the same substitution file is used for all SXR undulators and the same executable is used for all HXR undulators. All device-specific information such as offsets or calibration coefficients is specified in configuration files and loaded at IOC boot time. This approach allows to avoid over-relying on autosave and restore functions while maintaining a single version of the functional code. It also allows to minimize the number of code changes when a bug is fixed, or a new feature is added. The same approach was applied to user displays. A single set of display files was created and is loaded for each cell through macros. The same colour and information organization scheme was also used in the displays for each line to simplify locating information and operators training.

UNDULATORS COMMISSIONING AND OPERATION

Commissioning of the motion control system for the undulator line commenced in the Summer of 2019. The modular design of the hardware and software allowed the control system commissioning team to work in parallel with the undulators installation and metrology teams. It also allowed the controls team to simultaneously work on devices at different stages of the checkout process. The commissioning effort relied heavily on formalized checklists to ensure consistency in the checkout process and to provide a unique place to record data. However, some of the most repetitive tasks were automated using scripts to minimize the risk of errors. For example, the calibration of the rotary potentiometers measuring the angular position of the cam movers for the undulator girders was automated through a Python script. The script allows to move each cam one full rotation while recording the voltage of the corresponding rotary potentiometer. A linear potentiometer measuring the vertical displacement of the girder is also used as a reference for the calibration. Once the data is collected, a linear fit is applied to the rotary potentiometer voltage versus cam angle data set. The coefficients are used in EPICS to calculate the cam angular position from the potentiometer voltages. Figure 3 is an example of the resulting calibration plot showing the linear and rotary potentiometer voltages versus the motor angle. The calculated linear interpolation coefficients are also shown.

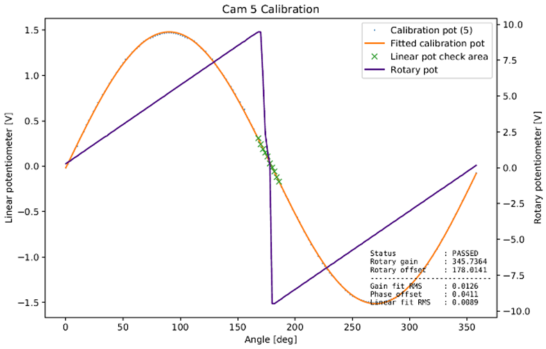

Figure 3: Girder rotary potentiometer calibration plot with calculated linear interpolation coefficients.

A similar script was created to automate the process of calibrating the linear potentiometers measuring the relative position between each SXR undulator segment magnetic axis and the vacuum chamber. During the calibration process, starting with the undulator centred on the vacuum chamber, a set of known displacements is applied manually to each linear potentiometer and the corresponding voltage is recorded. The automated script interacts with the users by prompting them to apply a specific displacement and then automatically recording the voltage. Figure 4 is an example of the calibration plot created.

Since the undulators were commissioned in 2020, features were added to improve robustness to the most common failure modes. For example, checks were added to prevent users from actuating the gap of an SXR undulator segment if its magnetic axis is not centred on the beam path. Also, as shown in Fig. 5, the displays were improved to provide more granular indications of the status of each cell and thus simplify investigations by non-experts. Documentation on how to use the devices and how to resolve most common issues or how to avoid them was also crated with the objective of training new engineers and accelerator operators.

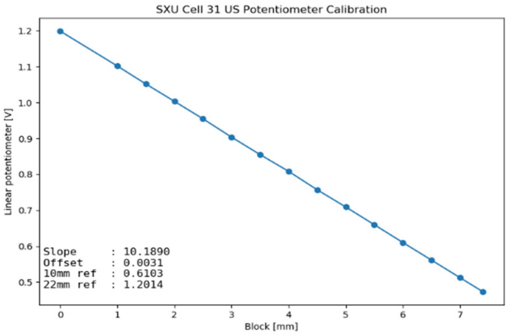

Figure 4: SXR Undulator segment linear potentiometer calibration curve.

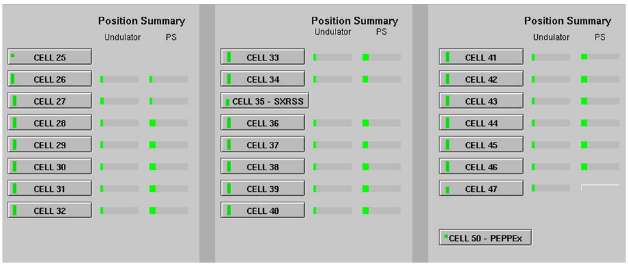

Figure 5: Undulator line overview display.

CONCLUSION

In this paper we have discussed the implementation and commissioning of the motion control system for the LCLS-II SXR and HXR undulators. The modular design was discussed, together with scripts for automated calibration of components. Future work will involve improving processes for automated detection and resolution of faults. Upgrades to the aging VME-based control architecture of the HXR undulators will also be considered.

ACKNOWLEDGMENT

The authors would like to thank all those involved with the physical installation of the undulators, their alignment, and their integration with other accelerator components.

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