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LCLS-II UNDULATOR MOTION CONTROL

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Abstract

At the heart of the LCLS-II are two undulator lines: the hard x-ray (HXR) line and the soft x-ray line (SXR). The SXR line is comprised of 21 variable gap undulator segments separated by an interspace stands with a cam positioning system capable of positioning in 5 degrees of freedom (DOF). The undulator segment motion control utilizes the Aerotech Ensemble motion controller through an EPICS Soft IOC (input-output controller). Its drive system consists of a Harmonic Drive servo system with feedback from two absolute full-gap encoders. Additional Aerotech motion controllers are used to control the cam-positioning system and phase shifters of the interspace stand. The HXR line is comprised of 32 undulator segments each including an integrated interspace assembly. The segment girder is placed on two stands with a similar cam-positioning system as in the SXR line allowing for movement in 5 DOF. As one of the design goals of the HXR line was to reuse the original LCLS girder positioning system, the motion control system is an upgraded version of that original system, using RTEMS on VME with Animatics SmartMotors.

OVERVIEW

This paper introduces the motion control design for the two LCLS-II undulator lines, the soft x-ray line (SXR) and the hard x-ray line (HXR). The motion control requirements of which are summarized in Table 1.

Table 1: LCLS-II Undulator Motion Control Requirements for both undulator lines.

Requirement	HXR	SXR	Unit
Minimum Undulator Gap	7.2	7.2	mm
Minimum Full Open Undulator Gap	120	200	mm
Taper Accuracy	±1.5	±2	µrad
Gap Repeatability	<1.5	<5	µm
Long term gap stability (24 hours)	±1	±1	µm
Maximum available full gap speed	1.0	1.0	mm/s

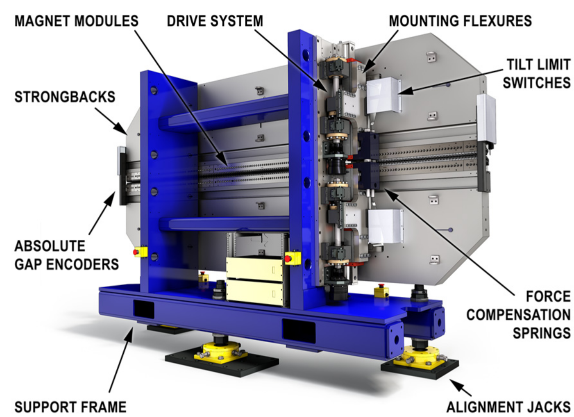

Figure 1: An LCLS-II Soft X-ray Undulator segment.

SXR LINE

The SXR line is comprised of 21 undulator segments separated by break sections, where each segment is a variable-gap permanent-magnet device with a minimum gap-height of 7.2 mm and a total segment length of 3.40 m [1, 2]. A single SXR undulator segment is shown in Figure 1. The gap drive system consists of four Harmonic Drive servo motors with feedback from internal rotary encoders and two full-gap encoders attached at each end of the undulator segment. Precise motion is achieved through the zero-backlash 51:1 strain wave gearing mechanism and is held in position with per-motor integrated brakes. Each break section in the SXR line consists of an interspace stand with a cam positioning system. Emergency stop circuits are intertwined between neighboring undulator sections and interspaces, such that the nearest emergency stop button can be used.

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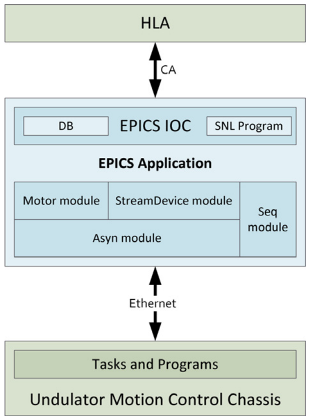

Figure 2: SXR software architecture overview.

Gap Motion Control

A 4-axis Aerotech Ensemble CP10 motion controller is at the center of the undulator segment gap motion control, driving each of the gap motors and closing the velocity and position loops on their respective encoders. Each undulator segment has an individual motion controller mounted to a rack on its support frame. Integration with the distributed control system and other high-level applications (HLA) is performed through an EPICS Soft IOC (input-output controller), relying on the EPICS collaboration Motor Module (as summarized in Figure 2 above) and asyn for communication with the device.

Synchronized motion is performed natively with the Aerotech Ensemble platform, though minor customizations to the motor record implementation were necessary to support deferred motion in model 2 drivers. Each servo motor has one EPICS motor record associated with it. Upon calculation of a new gap, taper, or center offset, by way of a State Notation Language (SNL) program:

1. New positions for each motor are calculated
2. Deferred moves are configured per motor, specifying target position, speed, and acceleration
3. A single synchronized motion command is generated and sent to the Aerotech controller
4. Motion continues until the gap is within the positioning deadband or a fault has occurred, in which case alarms are propagated up through the respective EPICS records

K-value to gap transformations are done on the EPICS record-level, utilizing spline-fit data from measurements done at the SLAC Magnetic Measurement Facility (MMF).

A set of 24 limit switches per segment are used to protect from various conditions: tilt detection, vacuum chamber proximity detection, end-of-travel detection, and over-travel detection. End-of-travel limit switches are monitored in a motion controller task, with custom logic that can allow motion in a certain direction to recover from a minor fault. Overtravel conditions are detected in the hardware circuitry. Actuation of such an overtravel or power switch immediately causes the amplifier power to be cut but still allows for logic power to go to the motion controller chassis for uninterrupted communication.

Since the vacuum chamber can be freely positioned between the interspace sections, potentiometers measuring the distance from the top jaw to the vacuum chamber are provided to the Beam Containment System (BCS) and Machine Protection System (MPS).

SXR Interspace

The interspace cam alignment system (as shown in Figure 4) has 5 degrees of freedom, allowing for full positioning of the phase shifters, quadrupole magnets, and RF cavity BPMs (below in Figure 3), along with the beamline vacuum chamber itself between interspaces.

To control the gap of the phase shifter (below in Figure 5) and the cam-positioning system of the interspace stand, an additional 6-axis Aerotech Ensemble motion controller is mounted to the interspace support post. This chassis hosts 5 Aerotech Ensemble MP10 drives for the cam stepper motor control and one Aerotech Ensemble CP10 for the phase shifter servo motor.

The cam alignment system is controlled by 5 Applied Motion HT23-series DC stepper motors, each with a rotary potentiometer for absolute position readback and a linear potentiometer for calibration. Cam alignment motion kinematics are calculated on the EPICS record-level.

The phase shifter control is comparatively simple, with a single Aerotech BM-series servo motor simultaneously moving both the top and bottom jaws through mechanical coupling. A Renishaw Resolute RL-series encoder is used for full-gap measurement feedback, and end-of-travel and overtravel limits are used in both directions.

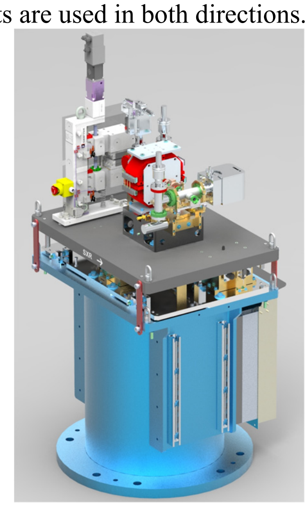
Figure 3: SXR interspace components on a pedestal, including from left to right: SXR phase shifter, quadrupole magnets, and RF cavity BPMs. The interspace motion controller can be seen mounted on the right of the pedestal.

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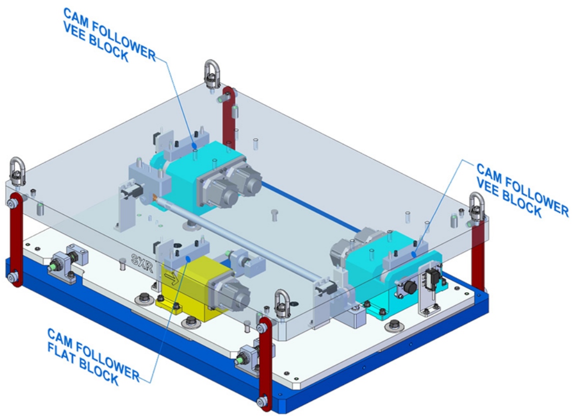

Figure 4: SXR interspace cam alignment system.

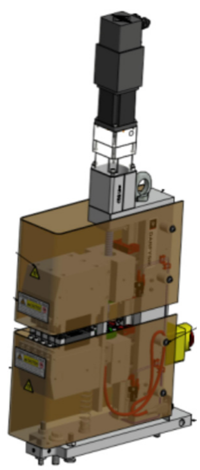

Figure 5: The SXR phase shifter system.

HXR LINE

The HXR line is comprised of 32 undulator segments (Figure 6) which include an integrated interspace assembly, holding a phase shifter, quad magnet and RF cavity BPM (beam position monitor). In contrast to the SXR line, the vacuum chamber is firmly attached to the girder of the variable gap undulator. The girder is placed on two stands each with a cam-positioning system similar to that of the SXR interspace stand allowing for movement in 5 DOF. Each of the HXR line segments is a variable horizontal gap, vertically-polarizing permanent-magnet device with a minimum gap-width of 7.2 mm and a total segment length of 3.40 m.

One of the design goals for the HXR line was to reuse as much of the original LCLS-I hardware as possible as a significant cost-saving measure. Due to this, the SXR control system and the HXR control system differ significantly. The software architecture described here is summarized in Figure 7.

Each segment has an independent VME crate with an MVME3100 single board computer running an EPICS IOC on RTEMS. The IOC communicates with other hardware via IndustryPack (IP) cards on Acromag AVME-9760 carriers. These IP cards include:

1. Acromag IP330 for analog-to-digital conversion of girder position potentiometers and temperature sensor readouts.
2. Acromag IP-OPTOIO for digital input and output.
3. Acromag IP520 for RS-232 communication to Animatics SmartMotors.
4. Acromag IP-EP201 with a custom FPGA implementation loaded by SoftGlue, described in a later section.
5. Tews TIP114 for reading the half- and full-gap absolute SSI encoders.

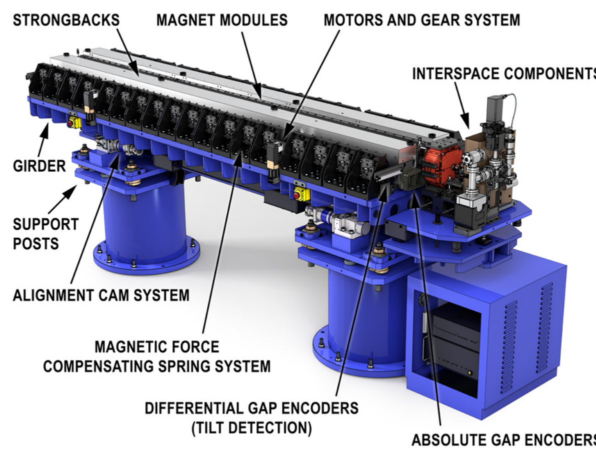

Figure 6: An LCLS-II Hard X-ray Undulator segment.

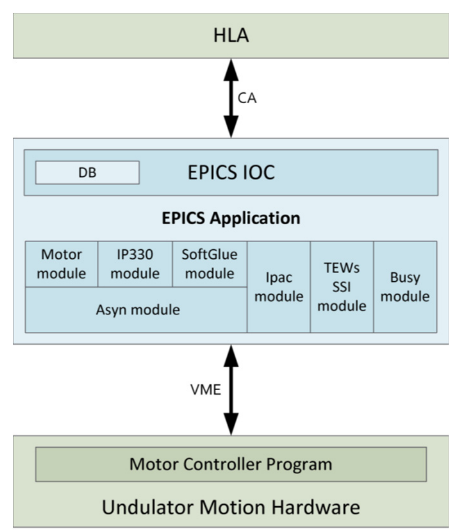

Figure 7: HXR software architecture overview, from high-level applications (HLAs) at the top to the undulator hardware at the bottom.

Gap Motion Control

Four Animatics SmartMotor SM23165DTs are used for the variable-gap translational stages, with 100:1 gear reduction, 5.08mm lead pitch screws, and integrated brakes and incremental encoders. Motion is performed in a multi-step approach, ensuring that the requested target position will not be overshot. The control system communicates with the master motor via RS-232 and it, in

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turn, communicates with the 3 slave motors over a CANopen fieldbus connection. A custom motion program running independently on each motor controller defines interrupt-driven subroutines to perform upon a movement request. From the top-level down, the procedure happens as follows:

1. A new gap, taper, or center value is requested.
2. New position values are calculated in EPICS and sent to each motor record as a deferred motion.
3. A virtual axis motor (representing the gap) record implementation transfers the calculated positions through a pre-determined set of variables to the master motion controller program.
4. The master motion controller program subroutine is called. It propagates the target positions to all slave motors, and broadcasts commands to release brakes and move in synchronization.
5. Throughout the process, the master motor is monitoring for heartbeat signals or error conditions from all slaves.
6. Brakes are re-energized after motion has completed.
7. The process is repeated until the gap has closed within the required deadband.

FPGA-based Interlock and Monitoring System

As a system with distributed motion controllers located directly on the undulator itself, none with direct electrical access to all limit switch information at one time, it was deemed necessary to build an interlock mechanism on top of the system. This comes in the form of an Altera FPGA on an IP-EP201 card in the undulator segment VME crate.

The FPGA firmware, analogous to the motion controller task running on the SXR motion controller, monitors the limit switch status and the absolute half-gap encoders for taper and asymmetry faults. It translates these conditions into simple clockwise and counter-clockwise limit switch signals that the individual motor controllers can interpret. This means that taper conditions can be recovered from if the firmware determines it is possible. The digital inputs, including the SSI encoder inputs, are routed through the IndustryPack Bridge to the Altera Avalon bus.

Additionally, the FPGA firmware monitors e-stop push button status, motor fuse status, and power supply status. These are strictly as monitors, as the amplifier power-cutting checks are done separately in hardware.

HXR Girder and Interspace Motion

The cam alignment system on the two undulator pedestals is shared with the HXR interspace, allowing for full positioning of the phase shifters, quadrupole magnets, and RF cavity BPMs (below in Figure 8).

As in the undulator gap motion, Animatics SmartMotors are again used here to control the cam-positioning system of the girder. This cam-positioning system remains from the LCLS, including all controls hardware. There are 5 axes per pedestal of SmartMotor SM2320D, each with one Novotechnik rotary potentiometer for absolute readback and one linear potentiometer for calibration.

The phase shifter (Figure 9) control is performed with a single SmartMotor SM23165DT servo motor simultaneously moving both the top and bottom jaws through mechanical coupling. An AMO absolute SSI encoder is used for full-gap measurement feedback, and end-of-travel and overtravel limits are used in both directions.

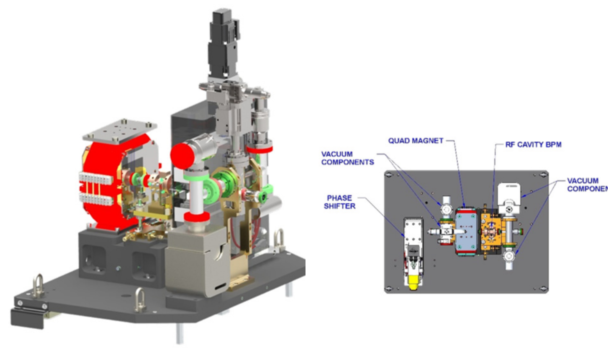

Figure 8: HXR interspace components, including RF cavity BPM, quadrupole magnet, vacuum components, and HXR phase shifter.

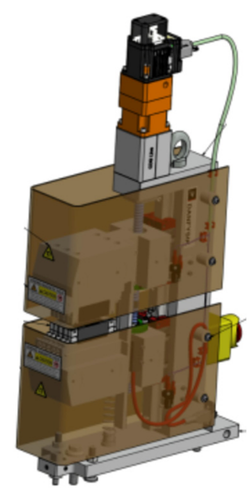

Figure 9: The HXR phase shifter.

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