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FAST WIRE SCANNER MOTION CONTROL SOFTWARE UPGRADE FOR LCLS-II *

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Abstract

LCLS-II is the first XFEL to be based on continuous-wave superconducting accelerator technology (CW-SCRF), with the X-ray pulses at repetition rates of up to 1 MHz. LCLS-II's wire scanner motion control is based on Aerotech Ensemble controller. The position feedback and the beam loss monitor readings during a wire scan aim to measure the beam profile. To meet the measurement requirements under both low and high beam repetition rates, we redesign the software program for EPICS IOC, Aerotech controller, and develop a new User Interface (UI) based on PyDM. This paper will describe the software development details and the software commissioning result under LCLS-II's production environment.

INTRODUCTION

The Linac Coherent Light Source II (LCLS-II) is a new X-ray Free-electron laser (XFEL) facility located at SLAC in California. It is the first XFEL to be based on continuous-wave superconducting (SC) accelerator technology (CW-SCRF), enabling it to deliver X-ray laser pulses that are 10,000 times brighter than those produced by the normal conducting (NC) linac [1]. Wire scanners are one of the primary diagnostic tools to measure the transverse profile of the electron beam at LCLS-II. The fast wire scanner has 3 wires with x, y, and u axes, assembled on an interchangeable card mounted on a linear motor stage [2, 3]. Figure 1 shows the fast wire scanner in the LCLS-II.

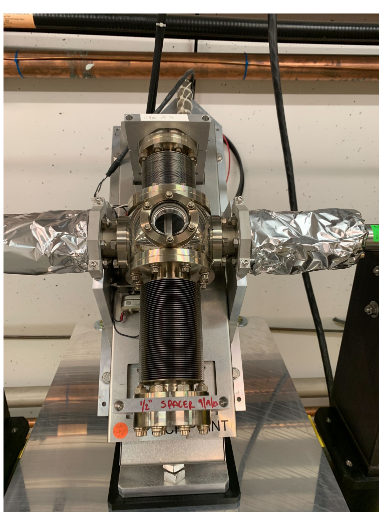

Figure 1: LCLS-II Fast Wire Scanner.

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Controlled by an Aerotech Ensemble controller, the fast wire scanner can rapidly intercept the beam while providing high-resolution beam profile on-the-fly. To reconstruct the transverse beam profile at different electron bunch repetition rates, which ranges from 1Hz to 1 MHz, the wire scanner must execute a varied range of scan profiles. Meanwhile, both NC linac and SC linac utilize the emittance diagnostic section in Beam Transport Hall(BTH) leading up to the Hard X-ray and Soft X-ray beamlines in the undulator hall. Therefore, it is essential for the fast wire scanner controls software in this region to be compatible with both the facilities.

To meet these new requirements, the motion control software program in EPICS and Aerotech controllers have been redesigned. In this paper, at first, we will define the design requirements in detail. The software development details, including the software architecture and design specifics, will be described in this paper. Additionally, the commissioning and field performance test results will be presented. Finally, ongoing work and future plans will be introduced.

MOTION CONTROL SOFTWARE DESIGN

Design Requirements:

In the existing SLAC linac tunnel, the LCLS-II system is equipped with 20 fast wire scanners that span from the RF Gun to the Beam-Transfer Hall (BTH). The schematic of LCLS NC and SC beamlines are depicted in Fig. 2,which showcases 6 out of the 20 newly installed fast wire scanners. NC and SC linac have the capability to deliver beam to the Hard X-ray beamline and the Soft X-ray beamline. Based on the desired beam path of NC and SC linac, the shared beamline sections of the emittance diagnostic region in the BTH receive different bunch patterns. Consequently, it is essential for the wire scanners in this shared beamline to be capable of automatically changing their scan modes based on the facility mode. To facilitate testing and debugging of software, a "local mode" is introduced that can read local simulated beam parameters in addition to the software having the ability to read global operating beam parameters.

Wire scanners are crucial for scanning beams with desired velocity to gather enough measurement points to obtain a beam profile. The wire scanner's desired moving velocity is calculated as [4, 5]:

$$v_{desired} = \frac{f_{rep} \times r_{wire}}{N_{desired}} mm/s \tag{1}$$

where r_{wire} is the scan range and $N_{desired}$ is the desired number of measurement points for each wire. Since the SC beam repetition rate can be continuously adjusted from 1 Hz

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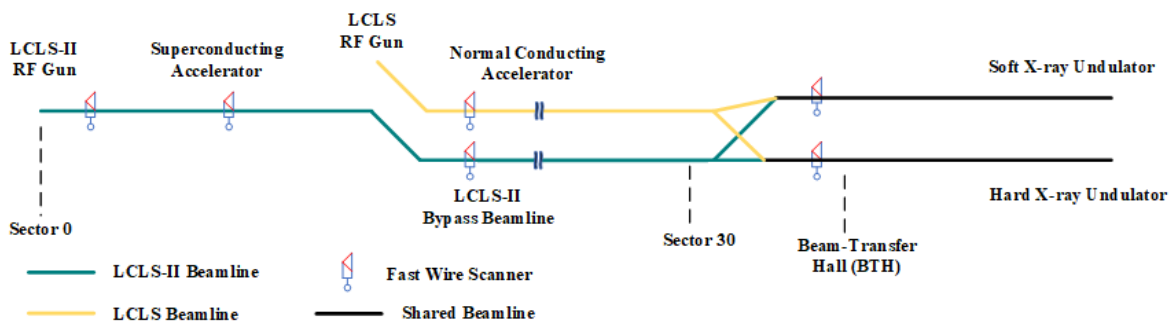

Figure 2: The Architecture of LCLS-II Beamlines.

to 1 MHz, the desired scan velocity should also be adjustable from $v_{desired}$ = 0.040 mm/s to $v_{desired}$ = 540 mm/s when the wire scan range and the scan points remain the same. As a result, 2 modes have been implemented for wire scanner: the step scan mode and the continuous scan mode.

In the scenario where the desired velocity is less than 10 mm/s, the wire scanner operates in step scan mode. In this mode, after a scan is initiated, the wire scanner will move at 10mm/s velocity between wires and at a velocity of $v_{desired}$ between the start and end position of the wire scan range. For all the other $v_{desired}$ greater than 10mm/s, the wire scanner will execute the continuous scan mode. In this mode, the motor will not slow down and stop between each wire range. The motor will move through the stage with the velocity defined by $v_{desired}$ in one continuous motion profile. Figure 3 illustrates the ideal scan trajectory of these 2 modes [4, 5].

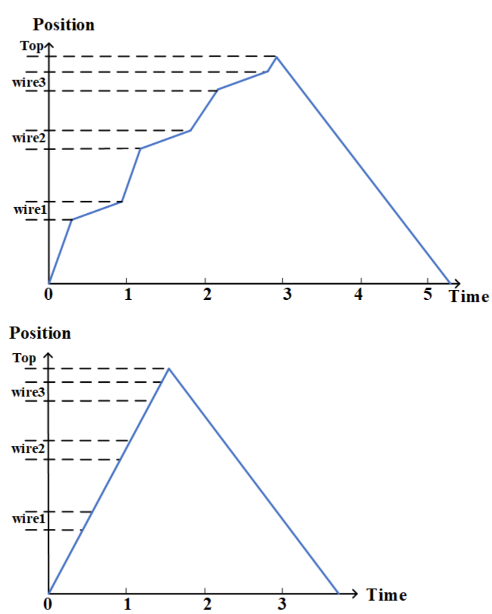

Figure 3: Step Scan Trajectory(Up) and Continuous Scan Trajectory(Down).

Furthermore, after the motor approached the top position, the subsequent homing or retracting velocity should be faster than the Machine Protection System (MPS) velocity, in case the wire scanner is burned by the electron beam. The MPS velocity is calculated as following [4, 5]:

$$v_{mps} = \frac{239 \times 2 \times f_{rep}}{600000} mm/s \qquad (2)$$

Software Architecture

LCLS-II fast wire scanner motion control consists of two layers: the Aerotech layer and the EPICS layer. Aerotech controller provides a high precision control of wire scanners' servo motors and communicates with EPICS Input/Output Controller (IOC) via Ethernet and TCP/IP. Figure 4 depicts the software architecture.

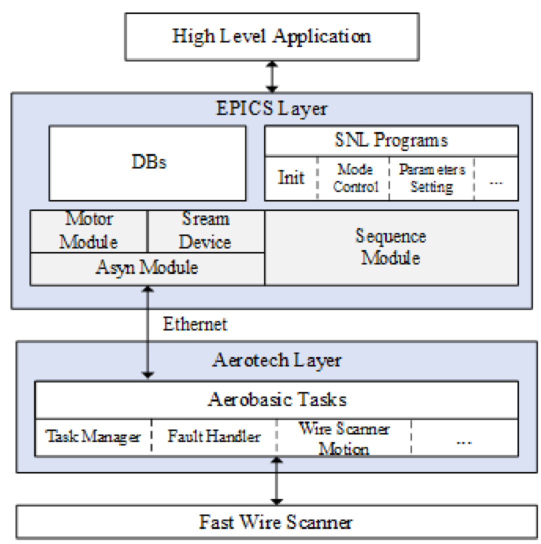

Figure 4: Fast Wire Scanner Software Architecture.

In the Aerotech layer, the controller provides at most five separate running cyclic tasks, each capable of including multiple functions. The management task listens to the scan start/stop command and calculated movement parameters from EPICS IOC. The motion task handles the main scan routine. In our new design, the move command in Aerotech Ensemble AeroBasic programs changes from previous absolute movement command to linear movement command for holding the velocity across the wire scan rage and meeting the performance intended [6]. Meanwhile, the fault handler

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function continuously monitors for any faults that may occur, such as over current and position error. In the case of a fault, it suspends the scan and recovers the motor after safely retracting the motor to home position. Additionally, the Aerotech controller can export signals such as motor position and velocity which can be retrieved to EPICS for subsequent scan performance analysis.

In the EPICS layer, a typical motor record is employed to handle motor movements. Stream Device based Database (DB) records are implemented to send AeroBasic commands supported over ASCII. By utilizing a multiple State Notation Language (SNL) program, the EPICS IOC can initialize the wire scanners, control scan modes, set parameters for Aerotech controller, and exchange data with High Level Applications (HLA).

Software Flowchart

When a scan is initiated, the wire scanner's IOC reads beam parameters in global mode. Based on the location of the wire scanner and the source of the beam (either NC or SC), the beam parameters are selected in this mode. Alternatively, the user can set test parameters in local mode. The scan velocity is calculated based on these parameters and transferred to the controller along with other necessary settings such as acceleration and deceleration for the requested scan velocity. Once start command is sent to the controller, motor torque will be activated. The controller continuously monitors for any motor fault, and reports the scan results and scan status to EPICS IOC upon completion. The software flowchart is shown in Fig. 5.

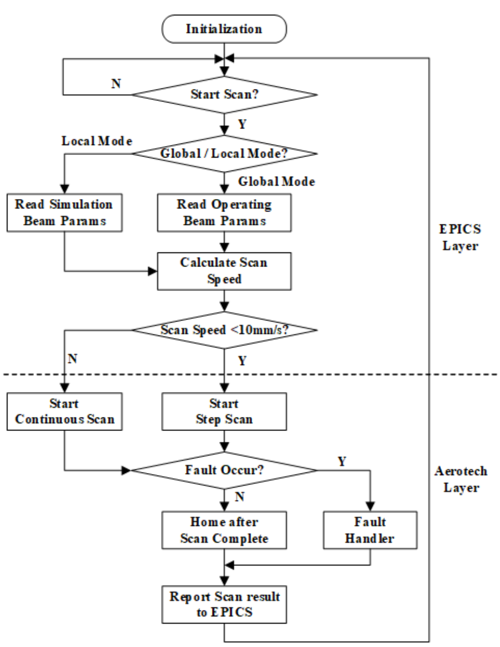

Figure 5: Fast Wire Scanner Software Flowchart.

We have designed a new user-friendly all-in-one User Interface (UI) based on PyDM as illustrated in Fig. 6. The main widget of the UI displays basic beam and scan parameters to provide users with essential information in a simple manner. Furthermore, 4 additional widgets are available for commissioning and troubleshooting purposes, offering access to expert-level data and functions when required.

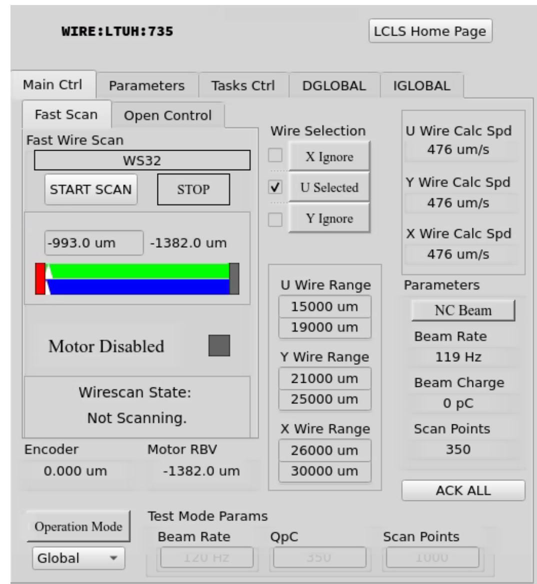

Figure 6: Fast Wire Scanner PyDM UI.

SOFTWARE COMMISSIONING

During the summer of 2023, the new programs for wire scanner controllers and EPICS IOC were deployed. Full commissioning and testing were conducted to ensure all functions can work as intended. All the 20 fast wire scanners motion control software in LCLS-II have been upgraded successfully. Aerotech Easy Tune was used to optimize servo gains for motor feedback loops. With this additional tuning, fast wire scanners can perform well in both step scan and the continuous scan mode. Figure 7 and Fig. 8 showcase the wire scanner movement from Aerotech Digital Scope program for these two modes.

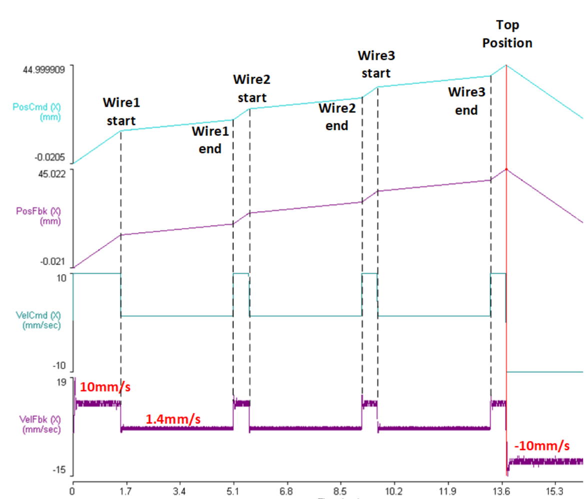

Figure 7: Step Scan With Velocity 1.4 mm/s.

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In the context of the two example scans, all the three wires are selected and the scan end position is set at 40 mm. The end of scan position for the third selected wire is 40 mm. To facilitate the stage to decelerate, stop, change direction of motion and accelerate back to the desired scan velocity, 5 mm is added to the end of scan position of the third wire. This results in a top position of 45 mm. As illustrated in Fig. 7, in the step scan, the wire scanner motor approached the start position for each wire at 10 mm/s velocity. Subsequently, it scans through the wire range at the velocity of 1.4 mm/s. The wire scanner takes approximately 13.7 mm to move to the top position and then returns back to the 0 mm (home) position at the velocity of −10 mm/s.

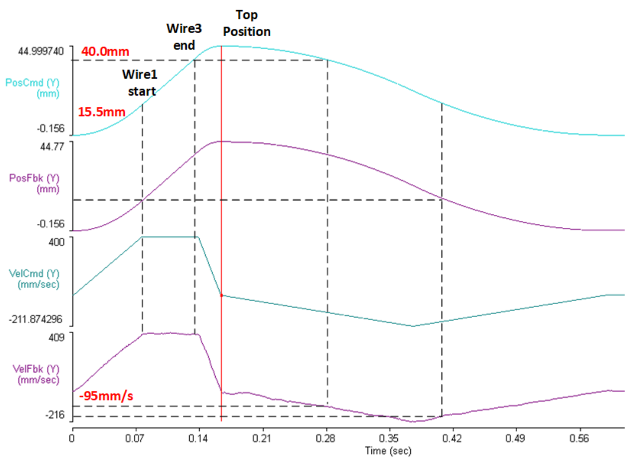

Figure 8: Continuous Scan With Velocity 400 mm/s.

In the continuous scan as shown in Fig. 8, the motor velocity can be accelerated to 400 mm/s at the start of wire 1 position (15.5 mm) within 77 µs. It then moved to the wire 3 end position (40 mm) at 400 mm/s and decelerated to 0 mm/s within 26 µs. During the wire scanner homing period between wire 3 end position and wire 1 start position, the motor velocity is at least −95 mm/s which is larger than v_{mps} (−79.7 mm/s), thus the beam will not burn the wires.

According to the scope data, the position feedback and velocity feedback can be traced back to the position command and velocity command for both step scan and continuous scan. The scope data profiles align with the ideal scan trajectory shown in Fig. 3, thereby fulfilling the design requirements.

FUTURE PLAN

Currently, monitoring and retrieving the scan profile requires a direct connection to the Aerotech controller, which is inconvenient for remote operation. To address this issue, a new data stream pipeline from controller to EPICS will be developed. This will aim to facilitate the collection and analysis of the motor movement scope data in EPICS side. Subsequently the data can be archived in EPICS. A scope data transfer function has been implemented as an AeroBasic task. This will allow retrieval of scope data on our remote server via a Python program. In our next step, we will develop programs to integrate scope data into EPICS, and ultimately provide a UI to display this functionality.

As of September 2023, the first light of LCLS-II has already been produced [7]. Consequently, we are now able to utilize the fast wire scanners in production environments, optimize software programs based on user feedback and any encountered issues.

CONCLUSION

In this paper, we described the design details of the upgraded motion control software for LCLS-II fast wire scanners. The upgraded system provides a wide range of scan velocity which is compatible with both low and high beam repetition rates. The scan performances have met the design requirements. All the fast wire scanner software in LCLS-II has been upgraded and they have been running stably for the past 2 months.

ACKNOWLEDGMENTS

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