DESIGN OF A PROTOTYPE PRECISION POSITIONING SYSTEM FOR THE UNDULATORS OF THE LINAC COHERENT LIGHT SOURCE*

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Abstract

A precision positioning system has been designed for the Linac Coherent Light Source (LCLS) and a prototype system is being fabricated. The LCLS will use a beam-based alignment technique to precisely align all of the segments of the 131.52-m-long undulator line. The requirement for overlap between the electron beam and the x-ray beam, in order to develop and maintain lasing, demands that each quadrupole must be aligned within a tolerance of ±7 µm and that undulator axes must be positioned within 5 µm vertically and 10 µm horizontally. Five cam movers, each with an eccentricity of 1.2 mm, will allow adjustment of a cradle supporting the undulator, its vacuum chamber, a quadrupole, and a beam position monitor. An additional motion transverse to the beam axis allows removal of individual undulators from the beam path. Positioning feedback will be provided by a wire position monitor system and a hydrostatic leveling system.

INTRODUCTION

An essential part of the LCLS project is contained within the 131.52-m-long undulator hall consisting of 33 segments that make up the undulator line. Each segment includes an undulator, a quadrupole with built-in correctors, a beam position monitor (BPM) and the vacuum chamber. The requirements for precision positioning of each undulator segment are very demanding. In addition, the beam-based alignment technique requires the ability to transversely move any quadrupole together with the entire undulator segment. Below are some of the salient tolerance requirements from LCLS Specification #1.4-001, General Undulator System Requirements [1]:

Standard Effective K	3.4965±0.0005
Quad motion positioning accuracy	±7 µm
Maximum Quad motion range radius	1.2 mm
Short-term (10 h) BPM and Quad stability	±1 µm
Quad center long-term (2 month) stability	4 µm

Each undulator must be able to be moved off of the vacuum chamber from its initial alignment position (roll-away cycle) in order to allow the beam to pass through the vacuum chamber unaffected by any undulator-induced fields. An 80 mm travel range is required for this motion cycle, and the positioning repeatability on return to the initial alignment position must be better than 5 µm in the vertical direction and 10 µm in the horizontal direction.

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A very small 4.5 mrad cant angle between the undulator poles allows adjusting the K value for microtapering along the undulator length. By individually moving each undulator in the horizontal transverse direction, the proper K value can be achieved based upon the microtapering requirements and the initial magnetic tuning results.

In order to meet the design requirements, two independent remotely-controlled positioning systems are necessary. One system is required for beam-based alignment, and another system is required for K-value adjustment the roll-away cycle. To meet the positioning tolerance requirements both systems must be very rigid and stable.

POSITIONING SYSTEM DESIGN

A prototype of the precision positioning system for an LCLS undulator is detailed in Figure 1.

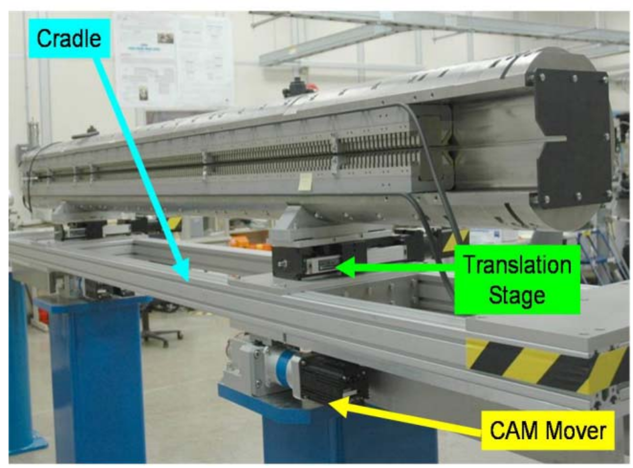

Figure 1: Prototype precision positioning system for the LCLS undulators.

The base of the mover system, referred to as the cradle, is made of two longitudinal and eight transverse 80 mm by 80 mm extruded aluminum bars. Supporting brackets are added to both ends of the cradle to provide additional rigidity. The vacuum chamber is rigidly mounted to the cradle, and the quadrupole and BPM are mounted to the cradle on manual short-travel translation stages used for initial alignment with respect to the undulator fiducials. Two translation positioning stages, each with a 4 inch travel range, are mounted on top of the cradle and directly support the undulator.

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The cradle assembly is supported on top of the two fixed bases through three cam-shaft movers. A double cam-shaft mover and a single cam-shaft mover are located adjacent to each other on one fixed base, and a double cam-shaft mover where the cams have been spread apart to for added stability is located on the other fixed base. Mounted on the bottom of the cradle, wedge block transition plates are used to contact the double cam-shaft movers and a flat block transition plate is used to contact the single cam-shaft mover. This arrangement provides ideal three-point kinematic support for the cradle assembly.

The cam-shaft mover system was first used at SLAC for the precise positioning of final focus components. A similar system is now in operation at the Swiss Light Source (SLS) for precision girder alignment. Due to tight positioning tolerance requirements, a similar design has been chosen for precise positioning of the prototype LCLS undulator [2].

After initial testing of the prototype motion system, several changes were made to the cam-shaft mover design. The cam-shaft eccentricity was changed to 1.5 mm for the single cam-shaft mover, and the eccentricity was changed to 1.2 mm for the double cam-shaft movers. The original double-row self-aligned spherical ball bearing was replaced with a standard double-row ball bearing with a spherical ring around it. In addition, the original 100:1 ratio standard gear box was replaced with a more precise gear box with less than 14 arc seconds of backlash. The new double cam-shaft mover is detailed in Figure 2.

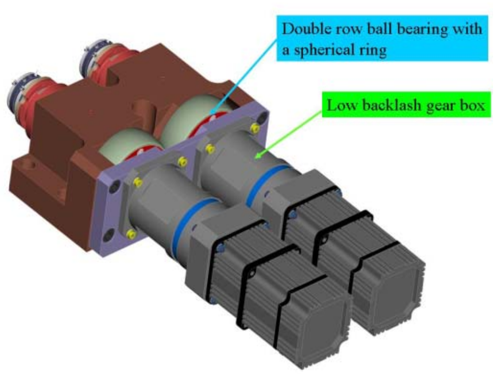

Figure 2: Double cam-shaft mover assembly.

EXPERIMENTAL TESTING PROGRAM

If the cradle is considered to be a rigid body and the Z dimension is defined to be along the path of the beam, the cradle can move under the command of the three cam-shaft movers with five degrees of freedom. The cradle assembly can move in the Y dimension (up and down), X dimension (side to side), and, depending on the relative motion of either end, the cradle can experience pitch, roll and yaw movements. The two translation positioning stages allow two degrees of freedom for the undulator with respect to the cradle assembly. The undulator can move in the X dimension, and, if the two translation positioning stages do not move exactly the same distance, then yaw will be introduced to the undulator with respect to the cradle assembly.

Due to tight precision positioning requirements, the testing method used to characterize the motion systems must have submicron resolution and stability. Furthermore, proper characterization requires that all independent degrees of freedom must be measured simultaneously and compared with the command control that drives the motion systems. Characterization of the cradle will require five simultaneous measurements, and characterization of the translation positioning stages will require two simultaneous measurements.

A new noncontact laser measurement product was recently introduced by Keyence Corporation that is well suited for this application. The new LK-G series high-speed, high-accuracy CCD laser displacement sensor uses triangulation for the measurement principle. As light is sent out of the sensor head the position of the reflected light on the linearized CCD moves as the position of the target changes. The displacement amount of the target is measured by detecting this change. The LK-G series sensor offers an order-of-magnitude better resolution than their previous product with the ability to achieve down to 0.01 µm resolution.

Cradle Measurements

To characterize the cam-shaft-driven cradle-mover system, five sensors are required to capture the possible five degrees of freedom of the cradle. Keyence LK-G37 sensors with a measurement range of ±5 mm and a resolution of 0.05 µm have been selected to perform the measurements. Relative to a fixed base, X dimension and Y-dimension measurements at both ends of the cradle will provide information on four degrees of freedom: pitch, yaw, X-dimension, and Y-dimension movements. A fifth sensor measuring the Y dimension on one side edge of the cradle will provide information on the fifth degree of freedom, roll.

In order to minimize alignment errors in the experimental setup, a scheme was chosen that will allow each sensor to be precisely aligned normal to a reference surface. A one-inch-square cube with two adjacent faces machined very flat and perpendicular to within ±10 arc seconds was chosen for the reference surface. At each end of the cradle, a reference cube is mounted on top of a miniature double goniometer, allowing common rotation about two orthogonal axes, and the goniometer assembly is mounted on top of a miniature rotational stage. The goniometers and rotational stage are used to initially align the reference cube to the cradle axis. A third cube is used for the reference surface for the fifth sensor measuring the Y-dimension displacement on one side edge of the cradle, but the rotational stage is not required for this setup.

Each laser displacement sensor is mounted on a double goniometer via an angle bracket. Sensor goniometers allow the laser beams to be precisely aligned perpendicular to a reference cube face in two orthogonal axes. Perpendicular alignment is achieved by adjusting each goniometer until the displacement value is minimized. The sensor goniometers are mounted onto a stiff angle bracket that is secured to the floor through a rigid pillar mount (see Figure 3).

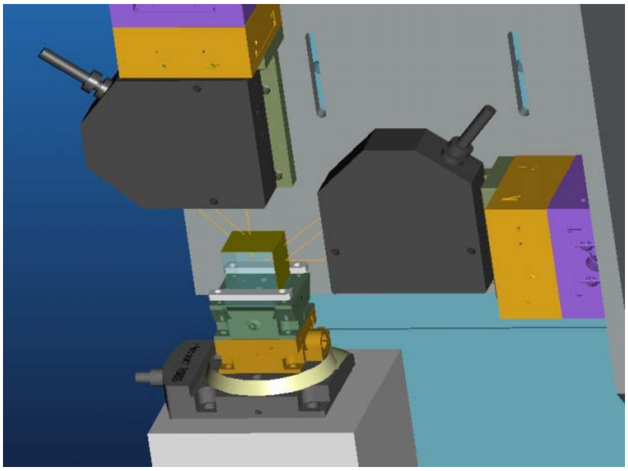

Figure 3: Reference surface and laser displacement sensor setup at the end of the cradle.

The reference cubes are mounted on top of stiff pillars at the position of the quadrupole and BPM relative to the cradle (see Figure 4). The measurements will therefore directly reflect the positioning tolerance of the quadrupole and BPM. All three reference cubes are placed at this height, thus all three Y-dimension reference surfaces are in a plane that is parallel to the cradle axis. This makes it easier to visually decipher the data during a motion prior to analyzing the data with software. Also, reference surface perpendicularity helps to correlate the X-dimension and Y-dimension measurements at each end of the cradle.

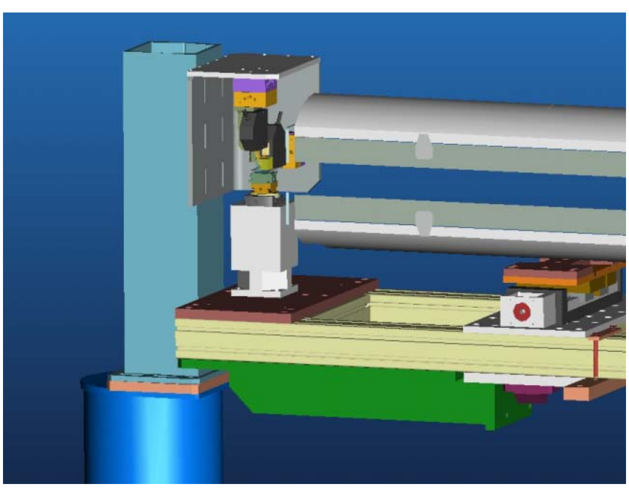

Figure 4: End view of cradle assembly with measurement equipment in place.

Measurement of Translation Positioning Stages

To characterize the two translation positioning stages used for the roll-away cycle, two sensors are required to capture the possible two degrees of freedom of the undulator with respect to the cradle assembly. Keyence LK-G157 sensors with a measurement range of ±40 mm and a resolution of 0.5 µm have been selected to perform the measurements. Less sensor resolution is required compared to the cradle measurements. Relative to the cradle, two X-dimension measurements on the back side of the undulator segment at both ends will provide information on two degrees of freedom: yaw and X-dimension movements.

On the back side of the undulator segment, two pre-existing flat-based notches used for mounting alignment fiducials will be used to mount two flat plates to serve as the measurement target surfaces. Two stiff angle brackets attached to the cradle frame are used to mount the measurement sensors. As before, each sensor is mounted on a double goniometer via an angle bracket allowing initial perpendicular alignment in two orthogonal axes.

DISCUSSION

Data from all of the sensors will be monitored and recorded using Labview-based data acquisition. Labview is also used to command and control the cam-shaft movers and the translation positioning stages; thus both the command data and measurement data will be monitored and recorded using the same system. Multidimensional calibration tables will be generated that will allow each of the mover systems to be characterized across their range of motion.

In addition to monitoring the measurement sensors, Labview will also be used to record data from up to 32 thermocouples. Type T bolt-on thermocouples will be placed at numerous locations along the undulator segment and cradle frame. The temperature of each of the motors and their immediate surroundings will also be monitored.

This measurement technique, compared to laser interferometry, is considerably easier to set up. The cost is also significantly less and atmospheric compensation is not required.

CONCLUSION

The first tests of the prototype LCLS undulator motion system recently began and initial results show, for both the cam-shaft mover system and the translation positioning system, that transverse translation seems to work very smoothly, with minimal vibration, and with no shock at the beginning and end of the travel ranges. In the next month or so the experimental program will be fully functional and the process of calibrating and characterizing the motion systems can begin.

REFERENCES

[1] LCLS Specification # 1.4-001, Revision 2, General Undulator System Requirements, March 2005.

[2] E. Trakhtenberg et al., “Undulator for the LCLS project – from the prototype to the full-scale manufacturing”, Nucl. Instrum. Methods A 543, 42-46 (2005).