LCLS-II-HE Phase Shifter Preliminary Mechanical Tests

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Abstract

The phase shifters for LCLS-II-HE will use the same mechanical structure as the LCLS-II SXR phase shifters. New magnet arrays, however, will produce stronger forces. In this note we study the behavior of the mechanical structure under the increased loads.

1 Introduction¹

The LCLS-II soft x-ray line (SXR) uses 20 phase shifters and their structural parts will be reused for LCLS-II-HE (SXR-HE). New magnet arrays will be added to the mechanical assemblies. In addition, 9 new phase shifter mechanical assemblies will be purchased and the new magnet arrays will be added to them. The SXR-HE line will have a total of 29 phase shifters.

The magnet arrays for the SXR-HE phase shifters will be larger and produce stronger magnetic fields than in the SXR phase shifters. At the minimum gap of 10 mm, the magnetic force on an SXR-HE magnet array is calculated to be approximately 310 pounds, while for an SXR magnet array, the force was calculated to be approximately 216 pounds². We wish to determine whether the mechanical structure of the SXR phase shifters can operate properly with the larger forces of the SXR-HE magnet arrays.

At this point in the phase shifter design, we don't yet have an SXR-HE magnet array. We can simulate the increased forces, however, by reducing the gap on an SXR phase shifter. In this note, measurements are presented with the reduced gap of an SXR phase shifter such that the forces are the same as the SXR-HE forces. The behavior of the mechanical structure is studied under the increased loads.

2 Test Objectives

The test results in this note are meant to address the following questions. With the stronger forces:

1. Is the drive system capable of changing the gap at the required speed?

¹Work supported in part by the DOE Contract DE-AC02-76SF00515. This work was performed in support of the LCLS project at SLAC.

²Z. Wolf, "A Phase Shifter Design For LCLS-II-HE", LCLS-TN-21-2, January, 2021.

- 2. Can the gap be set with the required accuracy?
- 3. Are all components operating within their specifications?
- 4. Are there any signs of lifetime reduction?

3 Requirements

The LCLS-II-HE phase shifter requirements come from a Physics Requirements Document³ and a technical note⁴. The requirements related to the mechanical system are briefly summarized below.

- 1. The phase shifter gap must reach a minimum value of 10 mm where the calculated force on each magnet array is approximately 310 pounds.
- 2. The accuracy for setting the gap must be better than 8 microns if the error on setting the gap is the only error. When temperature errors, alignment errors, and calibration errors are also considered, the tolerance for setting the gap is smaller. A formal error analysis has not been performed, but for this note we distribute the errors equally among the four sources and require the accuracy for setting the gap to be 8 microns $\div \sqrt{4} = 4$ microns or better.
- 3. The phase shifter gap speed must be 3x faster than the undulator gap speed during an energy scan. The current undulator gap speed is 0.2 mm/s, so the phase shifter gap speed must be at least 0.6 mm/s.

4 Mechanical Analysis

The phase shifter uses an Aerotech BM75-UF motor. The motor driver is Aerotech Ensemble CP. There is a 10:1 gear reducer between the motor and the lead screw. The pitch of the lead screw is 5 mm. Relevant parameters are listed below.

Motor stall torque	$0.51 \ \mathrm{Nm}$
Motor rated speed	4000 rpm
Motor rated power	$192 \mathrm{W}$
Gear reducer	10:1
Lead screw pitch	$5 \mathrm{mm}$

The maximum power that goes into opening the jaws is

$$P_{\max} = F \frac{dg}{dt} \tag{1}$$

where F is the force on a single jaw, and dg/dt is the rate of opening the gap. Note that a single jaw with force F acting on it moves at (1/2)dg/dt, so for two jaws, we have the

³D. Cesar et al., "LCLS-II-HE SXR Undulator System", LCLS-II-HE Physics Requirements Document LCLSII-HE-1.3-PR-0049-R0, August, 2020.

⁴Z. Wolf, "A Phase Shifter Design For LCLS-II-HE", LCLS-TN-21-2, January, 2021.

expression shown. Using F = 310 pounds = 1379 N, and dg/dt = 0.6 mm/s (from the requirements), we have

$$P_{\rm max} = 0.8 \ {\rm W}$$

This calculation does not include losses in the drive system, but it is far below the rated power of the motor.

The motor torque T is calculated using the energy supplied when the motor turns through an angle $d\theta_m$. We set this equal to the energy that goes into opening the gap.

$$Td\theta_m = Fdg \tag{2}$$

The motor angle is related to the screw angle by

$$d\theta_m = R d\theta_s \tag{3}$$

where R is the gear reducer ratio, which in this case is equal to 10. The ratio of the gap change to the screw angle change is given by

$$\frac{dg}{d\theta_s} = 2P \tag{4}$$

where the factor of 2 comes from both jaws moving, and the constant P is the pitch of the lead screw

$$P = \frac{5 \text{ mm}}{2\pi} \tag{5}$$

Putting these quantities together, we find

$$T = F \frac{dg}{d\theta_m}$$

= $F \frac{dg}{d\theta_s} \frac{d\theta_s}{d\theta_m}$
= $F 2P/R$ (6)

Putting in numbers, we find

$$T = (1379 \text{ N})2\left(\frac{0.005 \text{ m}}{2\pi}\right) \div 10$$
 (7)

$$= 0.22 \text{ Nm}$$
 (8)

If we include an efficiency of 0.9 for the gear reducer and 0.8 for the slides, we find the required motor torque to be

$$T_{req} = 0.31 \text{ Nm} \tag{9}$$

This is below the rated stall torque of the motor, which is 0.51 Nm. Further analysis will be required if the SXR-HE phase shifter is operated at smaller gap since the motor is not far from stalling.

We wish to know the motor speed if the gap is opened at 0.6 mm/s. From the formulas above

$$\frac{d\theta_m}{dt} = R \frac{d\theta_s}{dt}
= R \frac{1}{2P} \frac{dg}{dt}$$
(10)

Putting in numbers, we find

$$\frac{d\theta_m}{dt} = 10 \frac{1}{2\left(\frac{5 \text{ mm}}{2\pi}\right)} (0.6 \text{ mm/s})$$

$$= 1.9 \text{ rad/s}$$

$$= 0.3 \text{ rev/s}$$

$$= 18 \text{ rpm}$$
(11)

This is much slower than the rated speed of the motor.

The final question we wish to answer is whether the phase shifter structure will have any significant deformations under the increased loads. The phase shifter forces and relevant dimensions are shown in figure 1. The vertical magnetic force on the magnet arrays is

$$F = 310 \text{ lbs} = 1379 \text{ N}$$
 (12)

This force is counteracted by the lead screw which exerts the same force F in the opposite direction on the magnet jaw assembly. The moment produced by the vertical forces is

$$M = (1379 \text{ N})(0.110 \text{ m})$$

= 152 Nm (13)

The moment is counteracted by the slide. We model the slide as exerting forces f at its extremities. The force f is given by

$$M = f(0.078 \text{ m})$$

$$f = 152 \text{ Nm} / 0.078 \text{ m} \tag{14}$$

= 1949 N (15)

The forces are applied to the strongback and tend to bend it. The forces f in the figure are the forces on the jaw. The forces on the strongback are the negatives, -f. A model of the forces applied to the strongback is shown in figure 2. Tooling balls on the back of the strongback are indicated in red in the figure. For the beam bending calculation in this note, the strongback is along the x-direction and the bending is in the y-direction. For all other discussions in this note, the y-direction is vertical and the x-direction is from the strongback to the magnet arrays.

The equation governing the bending of the beam is given by

$$\frac{d^4y}{dx^4} = \frac{f_l}{EI} \tag{16}$$

where x is along the strongback, y is the deflection, f_l is the force per unit length modeled as delta functions, E is the modulus of elasticity for aluminum, and I is the area moment of inertia of the rectangular beam. Putting in the appropriate values, we find the deflections shown in figure 3. The middle tooling ball of the phase shifter moves approximately 5 microns toward the jaws, and the top tooling ball moves approximately 37 microns toward the jaws.The angle between the line from the upper to the middle tooling ball, and the line



Figure 1: Phase shifter forces and relevant dimensions.

from the middle to the lower tooling ball, is approximately

Bend Angle
$$\simeq \frac{.037 \text{ mm} - .005 \text{ mm}}{.37 \text{ m}} - \frac{.005 \text{ mm}}{.37 \text{ m}}$$

= .073 mrad

The tooling ball positions are compared to CMM measurements below. Both the tooling ball motions and the bending angle are very small, showing that the strongback is adequate for the increased magnetic forces.



Figure 2: Forces on the strongback, with the strongback in the x-direction and the deflection in the y-direction.



Figure 3: Calculated deflection of the strongback.

5 Mechanical Tests

The steps in this test were carried out using an SXR phase shifter. The gap is reduced below the normal operating limits in order to simulate the SXR-HE magnetic forces. A plot of calculated force vs gap is shown in figure 4. When the gap is reduced to 7.0 mm, the force is equal to the 310 pound force calculated for the SXR-HE phase shifters at 10 mm gap.



Figure 4: Calculated force on a jaw of an SXR phase shifter as a function of gap.

5.1 General Operation

The phase shifter performed the test without incident. The gap was closed to 7 mm and the motor had no problem to open it. For all gap changes in this test, the speed of the gap change was 1.5 mm/s, which is higher than the required speed. In continuous operation, the motor temperature rise was a small 5 deg C. No problems were detected in the general operation of the phase shifter.

5.2 Structure Deflections

Structural deflections of the phase shifter were measured on the CMM. First the gap was opened to 100 mm. The positions of all the tooling balls were measured. The tooling ball locations are shown in figure 5 along with the coordinate directions. The 100 mm gap tooling ball positions determine the baseline for deflections.

The phase shifter gap was then closed to 7.0 mm. All the tooling ball positions were again measured. The measurements were compared to the 100 mm gap measurements in



Figure 5: Tooling ball locations on the SXR phase shifter under test.

order to determine deflections of the structure. A summary of the changes is given in the following table.

	100 mm gap	$7 \mathrm{mm} \mathrm{gap}$	Change
Jaw Cant Angle (mrad)	-0.534	-2.289	-1.755
Jaw Taper Angle (mrad)	1.908	1.281	-0.627
Strongback Bend Angle (mrad)	0.042	0.134	0.092

The jaw cant angle is defined as the change in gap per change in x. All the tooling balls on the jaws were used in the calculation, so the cant angle is an average value referred to the center of the phase shifter in z. The jaw taper angle is defined as the change in gap per change in z. Again, all the tooling balls on the jaws were used in the calculation, so the taper angle is an average value referred to the center of the jaws in x. The strongback bend angle is defined as the change in angle between the line formed by tooling balls 15 and 14, and the line formed by tooling balls 14 and 13.

The tolerance on the jaw cant and taper angles is 20 mrad. The values of the angles are well below the tolerance. The strongback is stiff enough that its deflection under the increased load is insignificant.

Comparing the CMM measurements to the model given above, the center tooling ball in the middle of the strongback moved in x by 10 microns, while the model predicted 5 microns. The top tooling ball moved in x by 43 microns, while the model predicted 37 microns. The angle of the line between the top and middle tooling balls compared to the line between the middle and bottom tooling balls is 0.092 mrad, while the model predicted 0.073 mrad. Mechanically, the phase shifter is behaving approximately as expected, and is mechanically adequate for the increased loads.

The jaw cant angle is much larger than the amount the strongback is bending. This means that the slides are rotating under the moment. The slides are Schneeberger type

BM WR Size 25. The datasheet did not give a rotational rigidity specification. Since the cant angle is much smaller than the tolerance, the slides appear adequate for the increased loads. Note, however, from the photos of the phase shifter that the gap encoder is not at the beam position in x. Rather, the gap encoder is 75 mm away from the center of the magnet array. If the cant angle changes after calibration, the gap at the beam position will change, and the phase shifter calibration will change. The change in gap will be

$$\delta gap = (75 \text{ mm})\delta cant \tag{17}$$

where $\delta cant$ is the change in cant angle. A 0.1 mrad change in cant angle will change the gap at the beam position relative to the encoder by 7.5 microns, causing the phase shifter to go out of tolerance. So although the angular deflection of the slides is acceptable, 5% changes in the angular deflection cause the phase shifter to go out of tolerance. The design approach to use an encoder offset from the gap center relies heavily on the slides not changing after the phase shifter is calibrated.

5.3 Repeatability

The repeatability of setting the gap was measured on the CMM. All tooling ball positions were measured when the gap was set to 7.0 mm, 7.5 mm, 8.0 mm, 8.5 mm, 9.0 mm, 9.5 mm, 10.0 mm, 35 mm, 10.0 mm, 9.5 mm, 9.0 mm, 8.5 mm, 8.0 mm, 7.5 mm, and 7.0 mm. This set of measurements was repeated 5 times. This produced a large dataset which we now summarize.

When the gap was set to a given value, all the tooling ball positions were measured both as the gap was on the opening part of the cycle, and when the gap was on the closing part of the cycle. Since the x-position, for instance, of each tooling ball is different, we only consider changes relative to the first measurement. Figure 6 shows the change in x-position of all the tooling balls when the gap was set to 7.5 mm. The gap-opening measurements are given on the integer cycle numbers, and the gap-closing measurements are given on the half integer cycle numbers. Note that the position changes are very small, near the limit of what the CMM can measure.

When the above plot is repeated for all gaps, we get an overview of how the mechanical frame of the phase shifter changes over time during cyclic loading. The x-position change of each tooling ball at all gaps relative to the first measurement at each gap is shown in figure 7. Note that the phase shifter structure is very repeatable under cyclic loading with x-position changes less than 2 microns. This plot is repeated for y-position changes in figure 8, and for z-position changes in figure 9. The y-position changes are all less than 2 microns. The z-positions changes are up to 4 microns, but the phase shifter is thin in the z-direction so the mounting is not as stable.

The primary quantity of interest is how repeatable the gap is under cyclic loading. Figure 10 shows the repeatability of the gap during the 5 cycles of the test. The gap was calculated as the average y-position of the 4 tooling balls over the magnets on the upper jaw, minus the average y-position of the 4 tooling balls under the magnets on the lower jaw. Changes are shown relative to the first measurement at each gap value. Note that there is some hysteresis between opening and closing the gap, but it is small at the 1.5 micron level.



Figure 6: Change in tooling ball x-positions when the gap was at 7.5 mm during the 5 cycles of the test.



Figure 7: Change in tooling ball x-position at all gaps relative to the first measurement at each gap.



Figure 8: Change in tooling ball y-position at all gaps relative to the first measurement at each gap.



Figure 9: Change in tooling ball z-position at all gaps relative to the first measurement at each gap.



Figure 10: Changes in the gap during the cycling test.

5.4 Lifetime Test

A lifetime test was performed to see if the phase shifter changed during continuous use. Capacitive sensors were placed in the gap to measure the gap at 7.00 and 7.25 mm. Capacitive sensor measurements could not be made at larger gaps because of the limited range of the sensors. A photo of the capacitive sensors is shown in figure 11. The gap was set



Figure 11: Capacitive sensors were used to measure the gap during the lifetime test.

to the following values in a cycle: 7 mm to 10 mm in 0.5 mm steps, 10 mm to 35 mm in 1 mm steps, 35 mm to 10 mm in 1 mm steps, 10 mm to 7 mm in 0.5 mm steps, 7 mm to 100 mm to 7 mm. This is illustrated in figure 12. The lifetime test consisted of 500 cycles. The gap was set 21,000 times. Each time the gap was at 7.00 mm and 7.25 mm, the capacitive sensor readings were recorded. Temperatures of the phase shifter motor, jaws, and strongback were also recorded.

The phase shifter operated without incident during the lifetime test. The temperature of the motor rose by 5 deg C, as shown in figure 13, but this is a small temperature rise. Note that the program was interrupted twice during the test by network communication issues, and this is what caused the motor to cool down at 50 cycles and again at about 410 cycles. The top jaw is cooler than the bottom jaw because of the encoder read head mounted in the bottom jaw.

Each time the gap was at 7 mm, the capacitive sensors were read out. Since 7 mm was the smallest gap, this value was always approached while closing the gap. The capacitive sensor measurements relative to the first measurement are shown in figure 14. The resolution of the measurements is limited because the values were rounded off to the nearest micron in the data file. There appears to be a slow change in the gap of about 3 microns over 500 cycles.

The capacitive sensors were also read out when the gap was 7.25 mm. In this case



Figure 12: For each cycle of the lifetime test, the gap was set to the values in the figure.

readings were taken both while opening the gap and while closing the gap. The capacitive sensor measurements relative to the first measurement are shown in figure 15. The slow change in the measurements is present at 7.25 mm gap also. Friction changes in the slides might cause the gap to change since the drive screw is offset from the slide and the encoder is offset from the beam axis. When similar plots were made using only points with the gap opening and with the gap closing, they looked indistinguishable, but better resolution might be required to see any changes. It is possible that the capacitive sensors drifted, or the glue that was used to attach the sensors was shrinking over time. This test should be repeated when the SXR-HE magnet arrays arrive. Magnetic measurements can be made periodically during the lifetime test in order to determine if the phase shifter is actually changing.



Figure 13: Temperatures measured during the lifetime test.



Figure 14: Changes in the capacitive sensor measurements relative to the first measurement during the lifetime test.



Figure 15: Changes in the capacitive sensor measurements when the gap was 7.25 mm.

6 Conclusion

Initial tests were performed of the mechanical structure of the SXR phase shifters under the increased loads of the SXR-HE magnet structures. The increased loads were simulated by operating the phase shifter at smaller gap than normal. No significant deformations to the mechanical structure were observed under the increased loads. The drive system performed without incident, even at higher gap speeds than required. The phase shifter operated normally during the lifetime test. During the lifetime test, a slow gap change was observed, and this should be investigated further when the SXR-HE magnet structures arrive.