LCLS-II-HE Prototype Phase Shifter Test Results

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Abstract

Magnetic measurements were made on an LCLS-II-HE prototype phase shifter. All requirements were met. This note documents the results.

1 Introduction[1]

The SXR-HE line will have a total of 30 phase shifters, 29 in use and one spare. The mechanical frames of the 21 SXR phase shifters will be reused. Nine new mechanical frames will be purchased. Thirty new magnet arrays will be purchased. SLAC designed the magnet arrays[2] and SLAC will sort the magnets and tune and calibrate the phase shifters.

The first prototype magnet array arrived at SLAC in January, 2022. We installed the magnet array on the spare SXR phase shifter frame. We tuned the phase shifter and made many magnetic measurements. This note summarizes the results of the measurements.

2 Requirements

The LCLS-II-HE phase shifter requirements come from a Physics Requirements Document[3] and a technical note[4]. The requirements related to the magnetic performance are summarized below. The requirements must be met at all gaps in the operating range of 10 to 35 mm. The phase integral tolerances must be met on the beam axis. The field integral tolerances must be met for all horizontal and vertical positions within ±1.0 mm of the phase shifter beam axis.

1. The phase integral at 10 mm gap must be larger than 9500 T^2mm^3.

2. The phase change of the phase shifter must be accurate to 5.8° at all operational gap settings. Equivalently, the phase integral of the phase shifter must be accurate to

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

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

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

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

5.61 T^2mm^3. The phase integral will be measured at a discrete set of gaps. A fit to the measured phase integral vs. gap data must allow phase integrals at intermediate points to be know within the tolerance given here. This requirement sets the density of the measurements as a function of gap which must be made.

3. The change in phase integral in the range $x = \pm 0.3$ mm, $y = \pm 0.3$ mm of the beam axis must be below 5.61 T^2mm^3 in order for the phase integral to remain within tolerance with fiducialization and alignment errors.

4. The first field integral of B_x and B_y must be within $\pm 20 \times 10^{-6}$ Tm. The second field integral of B_x and B_y must be within $\pm 60 \times 10^{-6}$ Tm^2.

5. The change in the first field integrals due to neighboring devices must be less than 3 μTm. The 3 μTm change limit is used to define the fringe field length.

6. The fringe field length must be less than 144 mm.

3 Test Results

The measurements for these prototype tests follow the phase shifter test plan which will be used for the production measurements[5]. The test plan shows the measurement setup and describes how the Earth's field is handled. The test plan enumerates the set of measurements for the final dataset. The results of the measurements are presented below.

3.1 Phase Integral On Axis

The on-axis phase integral measurements are shown in figure 1. The phase integral at 10 mm gap, corrected to a temperature of 20.0 °C, is $10,030$ T^2mm^3. This is well above the required value of 9500 T^2mm^3.

Figure 1 also shows a spline fit to the measured phase integrals. Every other measurement was used in the fit. The residuals to the fit tell us whether we have enough measurements to accurately interpolate between points. The normalized residuals are shown in figure 2. The normalized residuals are less than 4×10^{-5}. The maximum absolute residual using a maximum phase integral of 10^4 T^2mm^3 is 0.4 T^2mm^3. This is well below the required limit of 5.61 T^2mm^3. The test plan has enough measurement points.

[5] Z. Wolf, Y. Levashov, H.-D. Nuhn, "LCLS-II-HE Phase Shifter Test Plan", LCLS-TN-22-2, January, 2022.

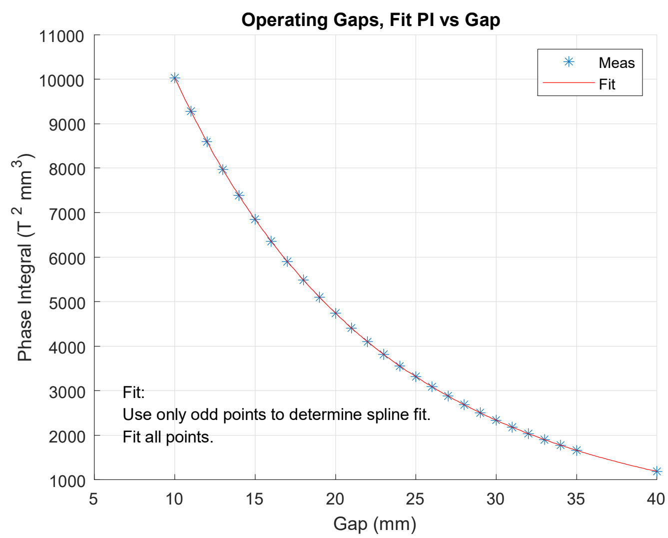

Figure 1: Phase integral as a function of gap.

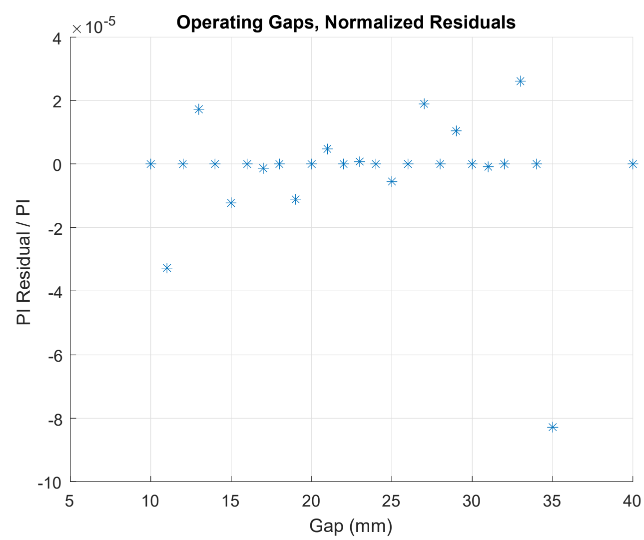

Figure 2: Residuals from a fit to the phase integral as a function of gap.

3.2 Phase Integral Off Axis

The phase integral as a function of x at 15 mm gap is shown in figure 3. Within a range of $x = \pm 0.3$ mm, the phase integral change is less than 1 T^2mm^3. This meets the requirement that the change be less than 5.61 T^2mm^3. The requirement is similarly met at all other gaps in the operating range.

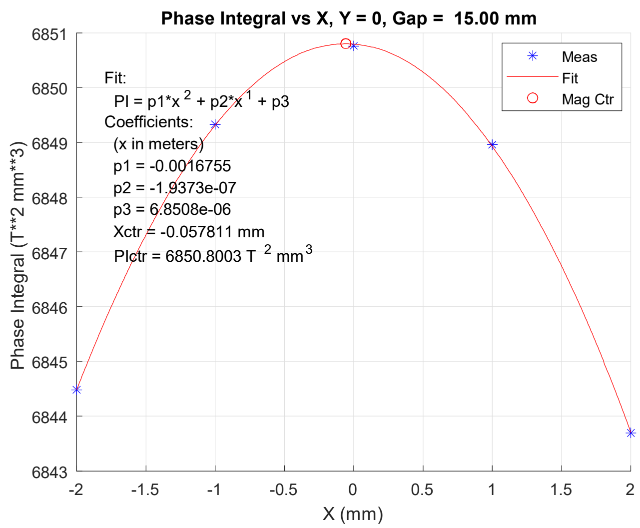

Figure 3: Phase integral as a function of x at 15 mm gap.

The phase integral as a function of y at 15 mm gap is shown in figure 4. Within a range of $y = \pm 0.3$ mm, the phase integral change is less than 5 T^2mm^3. This meets the requirement that the change be less than 5.61 T^2mm^3. The requirement is similarly met at all other gaps in the operating range.

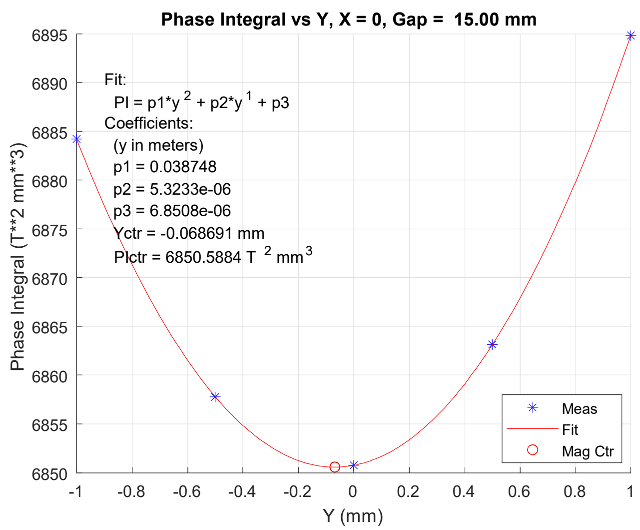

Figure 4: Phase integral as a function of y at 15 mm gap.

3.3 Field Integrals

The first integral of B_x as a function of gap is shown in figure 5. The first integral is within $\pm 20 \times 10^{-6}$ Tm over the entire gap range, not just in the operating gap range. The tolerance is met. The phase shifter is tuned at a single gap so the magnet sorting must keep the field integrals within tolerance at other gaps. Although the number of magnet blocks was limited for the prototype, it appears that the sort is adequate.

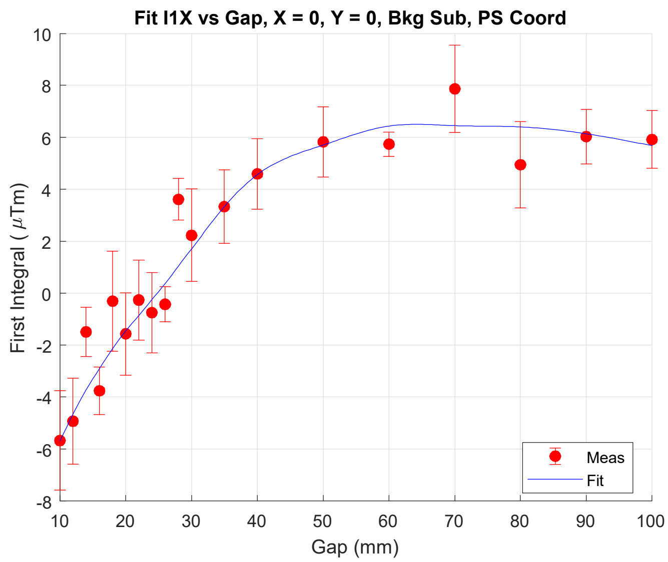

Figure 5: First integral of B_x as a function of gap.

The first integral of B_y as a function of gap is shown in figure 6. The first integral is within $\pm 20 \times 10^{-6}$ Tm over the entire gap range, not just in the operating gap range. The tolerance is met.

The second integral of B_x as a function of gap is shown in figure 7. The first integral is within $\pm 60 \times 10^{-6}$ Tm^2 over the entire gap range, not just in the operating gap range. The tolerance is met.

The second integral of B_y as a function of gap is shown in figure 8. The first integral is within $\pm 60 \times 10^{-6}$ Tm^2 over the entire gap range, not just in the operating gap range. The tolerance is met.

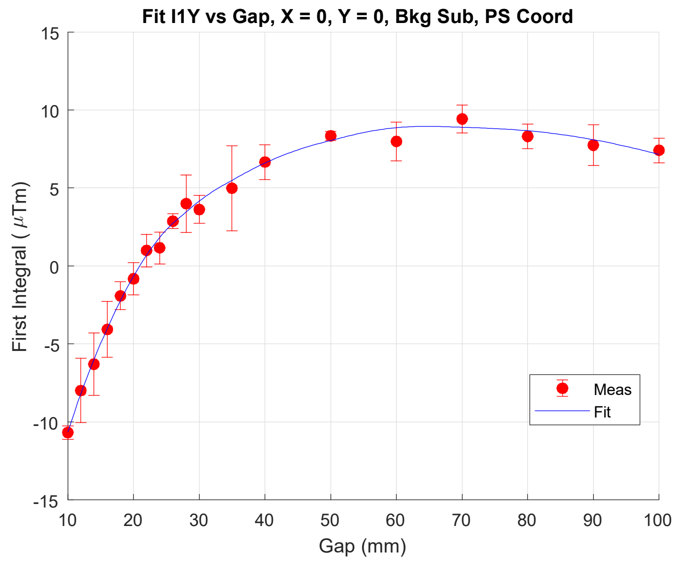

Figure 6: First integral of B_y as a function of gap.

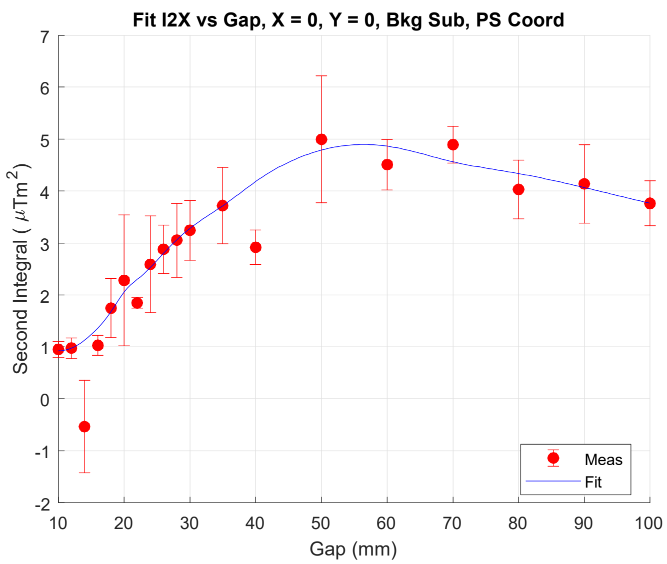

Figure 7: Second integral of B_x as a function of gap.

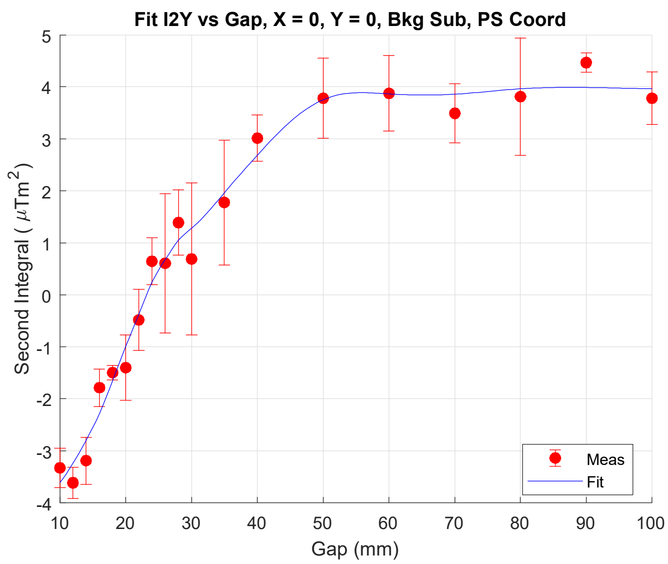

Figure 8: Second integral of B_y as a function of gap.

3.4 Fringe Fields

The fringe field length was determined using two methods. In the first method, Hall probe scans were used to find the locations where the first integral of B_y changed by 3 μTm compared to the end values. This gives the overall magnetic length of the phase shifter. The magnetic length as a function of gap is shown in figure 9. The magnetic length at maximum operating gap, 35 mm, is 365 mm. The phase shifter is 104.5 mm long. The fringe field length on each side of the phase shifter is then 130 mm. This is less than the required value of 144 mm.

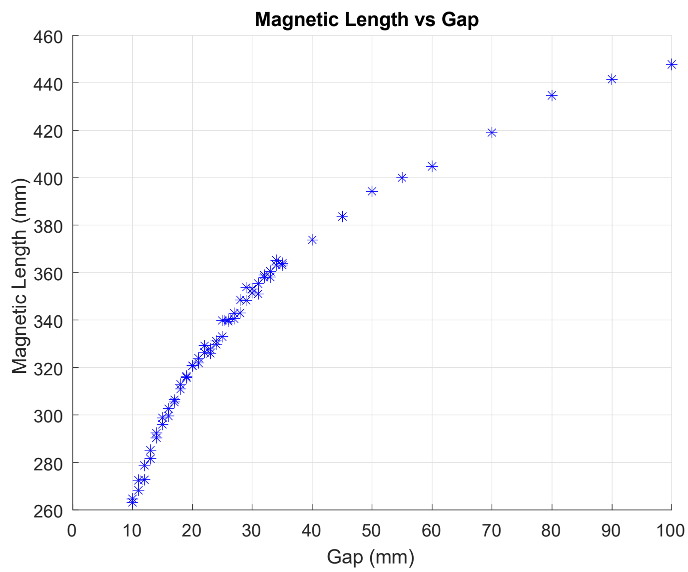

Figure 9: Phase shifter magnetic length as a function of gap.

The second method to determine the fringe field length used crosstalk measurements between the phase shifter and an undulator prototype section. The setup is shown in figure 10. The phase shifter is on a slide which is used to vary the distance between the phase shifter and the undulator prototype section. The first field integrals are measured with the long coil shown in the gap. The change in the first integrals of B_x and B_y as a function of the distance between the phase shifter and undulator section are shown in figure 11. At large distance, the field integrals don't change as the phase shifter is moved toward the undulator. However, at small distance, the first integral of B_y changes, indicating crosstalk. The change in the first integral of B_y is 3 μTm when the distance between the phase shifter and undulator is 130 mm. This gives a fringe field length of 130 mm, in agreement with the first method.

Figure 10: Setup used to measure phase shifter fringe field length.

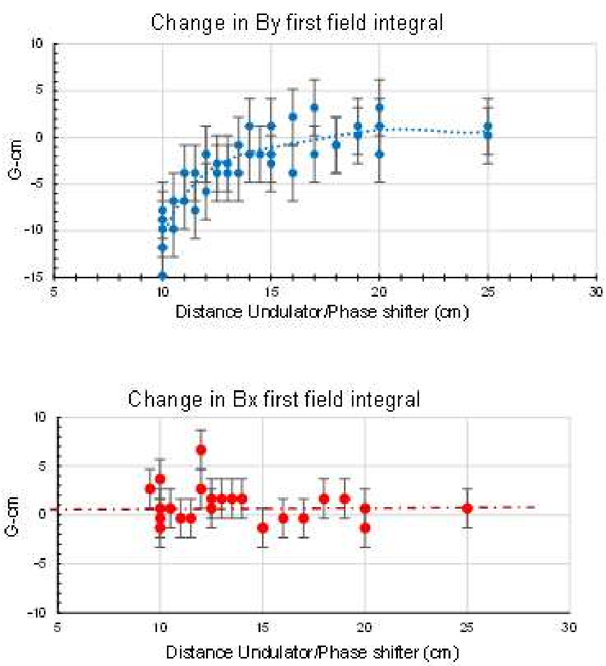

Figure 11: First integral of B_y and B_x as a function of the distance between the phase shifter and the undulator.

3.5 Lifetime Test

A lifetime test was performed on the prototype phase shifter. The gap was cycled 650 times and during each cycle, the gap was set 100 times according to the pattern shown in figure 12. The gap was set a total of 65,000 times.

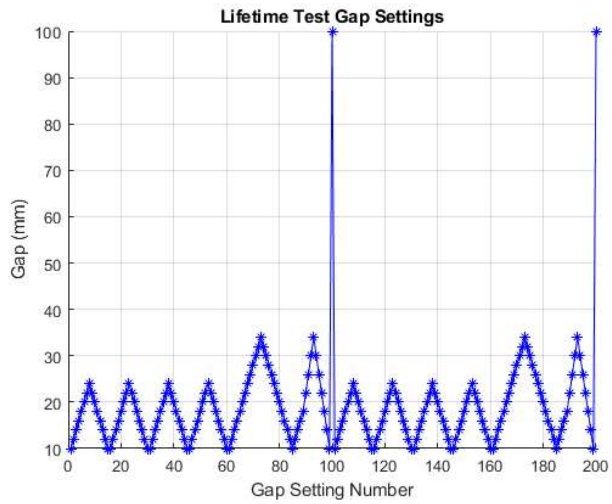

Figure 12: Pattern for setting the gap in the lifetime test.

Magnetic measurements were made after 90, 186, 250, 500, and 650 cycles. The change in phase integral at these cycle numbers is shown in figure 13. The change in phase integral is less than the tolerance limit of 5.61 T^2mm^3. The phase shifters have adequate lifetime to not require periodic recalibration.

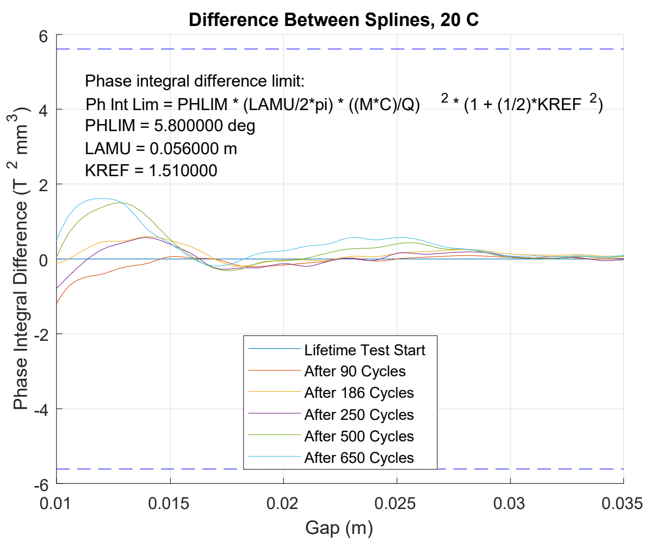

Figure 13: Change in phase integral during the lifetime test.

4 Conclusion

A prototype SXR-HE phase shifter magnet array was placed in an SXR phase shifter mechanical assembly according to the planned LCLS-II-HE upgrade of the SXR undulator line. A set of magnetic measurements was performed. The phase shifter met all the requirements. A lifetime test showed no use-related problems.