LCLS-II-HE Phase Shifter Test Plan

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Abstract

This note presents the test plan for the LCLS-II-HE soft x-ray phase shifters. For the LCLS-II-HE project, the existing 21 SXR phase shifters will have new magnet arrays installed. In addition, 9 new phase shifters will be built. All 30 phase shifters will need to be tuned and calibrated. In this note, the tuning and calibration steps for the phase shifters are detailed. Initially, a brief discussion of the measurement equipment is presented. The requirements for the calibration measurements are then summarized. A detailed tuning and calibration plan is presented in which each step is enumerated. Finally, the measurement results and data storage format are presented.

1 Introduction

The LCLS-II-HE project requires longer period undulators on the SXR line. The current 39 mm period SXR undulators will have their magnet arrays replaced with 56 mm period arrays. In addition, the undulator line will be lengthened by adding 9 new undulators, going from the current 21 undulators to 30 undulators. The SXR-HE undulators will have a larger range of $K$ values and this necessitates using stronger phase shifters. The current 21 SXR phase shifters (20 in active use plus one spare) will have their magnet arrays replaced with larger magnet arrays. In addition, 9 new phase shifters with new magnet arrays will be built. All 30 phase shifters will be tuned and calibrated at SLAC.

The plan for measuring the SXR-HE phase shifters is similar to the plan for measuring the SXR phase shifters\(^2\). A reference phase shifter will be selected and measured at frequent intervals in order to guarantee consistency of the measurements. The Hall probe used for the measurements will be frequently calibrated and the calibration will be checked in a reference dipole located on the test stand. Phase shifters which have been measured will periodically be brought back for repeat measurements to verify that the phase shifters are not changing due to storage conditions. A transportation test will be performed.

The note begins by describing the laboratory in which the work will be performed and the relevant equipment used for the measurements. The list of measurement and fiducialization requirements is then presented. This is followed by a detailed test plan in which all the steps of the measurements and fiducialization are enumerated.

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2 Measurement Facility

The magnetic measurements group will use the LCLS-II HXR bench to measure the phase shifters. The HXR bench is located in the Magnetic Measurement Facility (MMF). The laboratory has 0.1 °C temperature stability at a set point variable from 17 °C to 23 °C. The HXR bench is required to also be available for HXR undulator measurements. In order to accommodate both efforts, the phase shifter measurement system is built on an LCLS girder that sits on the pedestals that also hold the HXR undulators. The setup is shown in figure 1. Stages for stretched wire measurements are on either side of the phase shifter. The stretched wire system can be moved by the stages away from the Hall probe path to allow for the Hall probe measurements. On either side of the stretched wire system are zero gauss chambers. There is also a vertical field reference magnet, a fiducialization magnet, and a reference magnet where an NMR probe is used to check the calibration of the Hall probe.

![Figure 1: The phase shifters are measured on a girder at the HXR undulator bench.](image)

The phase shifters are handled with an overhead crane which is also shown in figure 1. The laboratory includes a complete set of instruments, calibration equipment, etc. Hall probe calibrations are done near the HXR undulator bench. Storage space for receiving phase shifters and for storing them until they are needed for installation is provided adjacent to the MMF. Storage space for the reference phase shifter will be provided in the MMF.
3 Earth’s Field

The effect of the Earth’s field on the phase shifter measurements requires some care since the background fields affect the field integrals and the phase integrals differently. Background fields add linearly to the field integrals, but add in a more complicated way to the nonlinear phase integral calculation. In addition, the background fields over the region of the phase shifter are included in the undulator measurements. They should not be double counted by including them in the phase shifter measurements. If we use background subtracted field measurements for the phase shifters, we include only the fields and field integrals from the phase shifter itself. This gives the correct added field integral from the phase shifter, but requires a small correction for the phase integral, as discussed below.

By using background subtracted field measurements, the orientation of the measurement bench with respect to the tunnel does not matter. The HXR bench orientation is parallel to the undulator lines, but the SXR-HE phase shifters at the HXR bench are rotated 180 degrees from their orientation in the tunnel. Without background field subtraction, the vertical component of the phase shifter magnetic field will add to the vertical component of the Earth’s field in the same way when the phase shifter is rotated; however, the horizontal component of the phase shifter field will subtract from the horizontal component of the Earth’s field at the HXR bench, but will add to the horizontal component of the Earth’s field in the tunnel. When we subtract the background fields from the measurements, only the fields from the phase shifter remain. The rotated bench orientation is not a factor.

The phase integral is given by

\[ PI = \int_0^L \left\{ \left( \int_0^z B_y(z')dz' \right)^2 + \left( \int_0^z B_x(z')dz' \right)^2 \right\} dz \]  

(1)

In this expression, the fields are the sum of the phase shifter fields \((B_{yps} \text{ and } B_{xps})\) and the background fields \((B_{ybkg} \text{ and } B_{xbkg})\). Inserting these component fields in the phase integral expression, we get

\[ PI = \int_0^L \left\{ \left( \int_0^z [B_{yps}(z') + B_{ybkg}(z')]dz' \right)^2 + \left( \int_0^z [B_{xps}(z') + B_{xbkg}(z')]dz' \right)^2 \right\} dz \]  

(2)

The contributions from the phase shifter fields and the background fields can be separated, but there is a cross term.

\[ PI = PI_{ps} + PI_{bkg} + PI_{cross} \]  

(3)

\[ PI_{ps} = \int_0^L \left\{ \left( \int_0^z B_{yps}(z')dz' \right)^2 + \left( \int_0^z B_{xps}(z')dz' \right)^2 \right\} dz \]  

(4)

\[ PI_{bkg} = \int_0^L \left\{ \left( \int_0^z B_{ybkg}(z')dz' \right)^2 + \left( \int_0^z B_{xbkg}(z')dz' \right)^2 \right\} dz \]  

(5)

\[ PI_{cross} = 2\int_0^L \left\{ \int_0^z B_{yps}(z')dz' \int_0^z B_{ybkg}(z')dz' + \int_0^z B_{xps}(z')dz' \int_0^z B_{xbkg}(z')dz' \right\} dz \]  

(6)

When the phase shifter is added in the tunnel, the additional phase integral is

$$\Delta PI_{tunnel} = PI - PI_{bkg}$$

(7)

or

$$\Delta PI_{tunnel} = PI_{ps} + PI_{cross}$$

(8)

This shows that if we use the background subtracted fields in the lab to calculate the phase integral $PI_{ps}$, we must add the correction $PI_{cross}$ to get the added phase integral when the phase shifter is installed in the tunnel.

In general $PI_{cross}$ will be small. We can make a rough estimate of $PI_{cross}$ by assuming that the background fields are constant over the region of the phase shifter, which is a good approximation for short phase shifters. In this case

$$\int_0^z B_{ybk}(z')dz' = zB_{ybk}$$

(9)

with a similar expression for $B_{xbk}$. The cross term becomes

$$PI_{cross} = 2\int_0^L \left\{ zB_{ybk} \int_0^z B_{yps}(z')dz' + zB_{xbk} \int_0^z B_{xps}(z')dz' \right\} dz$$

(10)

or

$$PI_{cross} = 2B_{ybk} \int_0^L zI1Y_{ps}(z)dz + 2B_{xbk} \int_0^L zI1X_{ps}(z)dz$$

(11)

where $I1Y_{ps}$ and $I1X_{ps}$ are the first field integrals of the phase shifter. Integrating by parts, we have

$$\int_0^L zI1Y_{ps}(z)dz = L*I2Y_{ps} - \int_0^L I2Y_{ps}(z)dz$$

(12)

where $I2Y_{ps}$ and $I2X_{ps}$ are the second field integrals of the phase shifter. There is a similar expression for $\int_0^L zI1X_{ps}(z)dz$. We approximate $I2Y_{ps}(z)$ to be a step function assuming the phase shifter is short compared to $L$. In this case

$$\int_0^L zI1Y_{ps}(z)dz \cong L*I2Y_{ps} - \frac{L}{2} I2Y_{ps}$$

(13)

$$\int_0^L zI1X_{ps}(z)dz \cong \frac{L}{2} I2Y_{ps}$$

(14)

Combining terms, we have

$$PI_{cross} \cong B_{ybk} L*I2Y_{ps} + B_{xbk} L*I2X_{ps}$$

(15)

In the next section we will see that the second field integrals of the phase shifter must be less than $60 \times 10^{-6}$ Tm². The background fields are approximately $B_{ybk} = -4 \times 10^{-5}$ T and $B_{xbk} = 2 \times 10^{-5}$ T. The length of the phase shifter fields is approximately $L = 0.4$ m. We take these as upper limits, so the cross term is less than

$$PI_{cross} < (60 \times 10^{-6} \text{ Tm}^2)(0.4m)(4 \times 10^{-5} - 2 \times 10^{-5} T)$$

(16)
This upper limit of $P_{I_{cross}} < 0.48 \, \text{T}^2 \text{mm}^3$ is small compared to the phase integral tolerance of 5.61 $\text{T}^2 \text{mm}^3$ (see below). We will ignore the cross term when doing the calibrations and only present the phase integral from the background subtracted fields as a function of gap. We will, however, use the nominal background fields of $B_{y_{bkg}} = -4 \times 10^{-5} \, \text{T}$ and $B_{x_{bkg}} = 2 \times 10^{-5} \, \text{T}$ to perform a check on all phase integral measurements that the cross term is small compared to the tolerance.

4 Measurement Requirements

4.1 SXR-HE Requirements

The LCLS-II phase shifter tuning and fiducialization requirements come from a Physics Requirements Document\(^4\). The list of tuning and fiducialization requirements is briefly summarized below.

The requirements below must be met for all gaps in the operating range of 10 to 35 mm. Additionally, the field integral tolerances given below must be met for all horizontal and vertical positions within $\pm 1.0 \, \text{mm}$ of the phase shifter beam axis at all gaps from 10 to 35 mm. The phase integral tolerances must be met on the beam axis.

1. The phase change of the phase shifter must be accurate to $5.8^\circ$ at all operational gap settings. Equivalently, the phase integral of the phase shifter must be accurate to $5.61 \, \text{T}^2 \text{mm}^3$. 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 known within the tolerance given here. This requirement sets the density of the measurements as a function of gap.

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

3. The phase shifter temperature at which all measurements are performed must be $20.0 \pm 0.5 \, \text{degrees Celsius}$.

4. The position of the beam axis must be known to $\pm 50 \, \mu\text{m}$ in $y$ and $\pm 200 \, \mu\text{m}$ in $x$ relative to tooling balls on the phase shifter.

4.2 Operational Requirements

We impose the following operational requirements.

1. The reference phase shifter must be measured and fiducialized after every 4’th phase shifter.

\(^4\)D. Cesar et al., "LCLS-II-HE SXR Undulator System", LCLS-II-HE Physics Requirements Document LCLSII-HE-1.3-PR-0049-R0.
2. A reference magnet at the bench must be measured with the Hall probe and this measurement compared to an NMR measurement before each final data set. The Hall probe must be recalibrated when its measurement relative to the NMR changes by more than $2 \times 10^{-4}$.

3. After measurements, the phase shifters will be stored until they are placed in the tunnel. Every three months, a phase shifter must be returned from storage and inspected and measured to verify that the storage conditions are not altering the phase shifter. Temperature and humidity must be logged in the phase shifter storage area.

4. One phase shifter must be used for a temperature test. The phase integral value will be measured over the range 18 °C to 22 °C in 1 °C steps. These measurements will be used to determine corrections to the gap settings for tunnel temperatures different than 20.0 °C.

5. One phase shifter will be transported to the LCLS-II tunnel and then returned to the MMF for re-measurement. This test is to ensure that phase shifter handling practices do not change the calibration.

6. One phase shifter must be used for a lifetime test. The gap will be cycled in a way which simulates approximately 10 years of operation. Hall probe measurements will be performed periodically during the cycling to check for any changes in the phase integrals or field integrals. These measurements will be used to find any potential lifetime related problems, and to determine the frequency of any required recalibrations.

5 Test Plan

5.1 Overview

All SXR-HE phase shifters will have new magnet modules that require tuning and calibration. This process will be done in several stages. When a phase shifter has its new magnet modules installed, an acceptance test will be performed establishing that the magnet block polarities are correct and that the phase shifter is operational. Limit switch settings will be made and the encoder offset value will be determined. Before tuning, the phase shifter must sit in a temperature stabilization area for at least one day. The phase shifter is then brought to the bench and mechanically aligned. Magnetic field measurements at different gaps then proceed. The magnet blocks are moved to shim the magnetic field. When the tolerances are met at all gaps, a final data set will be made and the phase shifter will be fiducialized.

A stretched wire will be used for overall field integral and field integral uniformity measurements. Hall probes will be used for the phase integral measurements. Small offsets will be removed in the Hall probe measurements using the field integrals from the stretched wire.

The phase shifter fiducialization will occur at the HXR bench using a laser tracker. A set of fiducialization magnets on the girder near the phase shifter will be used to determine the magnetic axis position.
A vertical field alignment magnet is used to set the probe angles. A reference magnet is used to check the Hall probe calibration. Each Hall probe measurement starts in a zero Gauss chamber and ends in a zero Gauss chamber. There is minimal field in these chambers, so any non-zero reading is due to offsets in the probe electronics. A linear fit is made to the beginning and end measurements in the zero Gauss chambers and the fit is subtracted from the measurements in the phase shifter as a zero offset correction.

Background field integrals are measured without a phase shifter using the stretched wire. These background stretched wire measurements are subtracted from the stretched wire measurements in the phase shifter giving the background subtracted field integrals. The background fields for the Hall probe are measured using the ends of the scan where the phase shifter fields are negligible. A linear fit is made to the background fields at each end, and the fit is subtracted from the Hall probe scan in the phase shifter. Since noise can affect the Hall probe background field determination, a small constant offset field is added to make the background subtracted first field integrals agree with the background subtracted stretched wire first field integrals.

5.2 Test Plan

1. At the start of production measurements, measure background fields at the HXR bench with the stretched wire

   (a) With no phase shifter in place at the bench, perform first and second field integral measurements at the nominal \((x, y)\) location of a phase shifter magnetic axis. The exact location does not matter, but it should be close to the phase shifter measurement axis.

   (b) Put the measurement data and analysis results in the Background folder discussed below in the Measurement Results section.

2. Preliminary phase shifter checks

   (a) All phase shifters must have their limit switch positions set and their encoder offsets set before measurements begin. The phase shifter must be protected and functional. Check the minimum gap with a ceramic block.

   (b) The phase shifter must be at \(20 \pm 1\) °C when it is brought into the laboratory. During the setup time and initial measurements, the phase shifter must come to a temperature of \(20 \pm 0.5\) °C.

3. Place the phase shifter at the HXR bench

   (a) Bolt the phase shifter to the girder at the HXR measurement bench.

   (b) Have the Controls group make all necessary wiring connections to operate the phase shifter. Test all limit switches.

   (c) Attach thermistors to the upper and lower magnet arrays to measure temperature.
4. Mechanically align the phase shifter to the bench

(a) Set the phase shifter gap to 30 mm so that the alignment crew can make laser tracker measurements in the gap.

(b) Have an alignment crew position the phase shifter so that the center of the magnet arrays is on the Hall probe measurement axis. Use the tooling ball sockets on the jaws and the nominal dimensions to set the center position. Touch several upper and lower magnets with the laser tracker target to confirm the centering.

(c) Take out pitch and yaw using the tooling ball sockets on the jaws and frame of the phase shifter. Use nominal dimensions from the drawings.

5. Find the magnetic axis

(a) Set the phase shifter gap to 15 mm.

(b) Define the Hall probe position to be \( x = 0, y = 0 \) on the nominal measurement axis.

(c) Measure the background subtracted phase integral at \( y = 0, x = -1, -0.5, 0, 0.5, 1 \) mm. No stretched wire corrections are needed.

(d) Find the x-position of the maximum phase integral. Let this position be called \( x_0 \).

(e) Measure the background subtracted phase integral at \( x = 0, y = -0.50, -0.25, 0, 0.25, 0.50 \) mm. No stretched wire corrections are needed.

(f) Find the y-position of the minimum phase integral. Let this position be called \( y_0 \).

(g) The position \( x_0, y_0 \) defines the magnetic axis relative to the nominal measurement axis.

(h) Translate the coordinate system so the new \( x = 0, y = 0 \) position is at the \( x_0, y_0 \) position.

6. Tune the phase shifter

(a) Set the phase shifter gap to 10 mm.

(b) With the Hall probe, measure the background subtracted fields on the magnetic axis \( (x = 0, y = 0) \). Calculate the block motions required to make the trajectory straight and make the first and second field integrals zero.

(c) Set the phase shifter gap to 100 mm. Move magnet blocks vertically and horizontally according to the calculations in step (b). Move upper and lower blocks equal amounts to keep the magnetic center on the magnetic axis. Only move blocks vertically away from the gap so that the minimum gap dimension is not reduced. Repeat steps (a) to (c) as needed.

(d) Make Hall probe measurements at gaps of 10, 12, 15, 20, 25, 30, 35 mm. Check that the background subtracted field integrals are within tolerance at all gaps. If they are not, choose a larger tuning gap and repeat steps (a) to (c).
(e) Make a set of background subtracted stretched wire measurements at gaps of 10, 12, 15, 20, 25, 30, 35 mm. Verify that the background subtracted field integrals are within tolerance at all gaps.

7. Final results data set

(a) Measure the gap of the phase shifter using capacitive sensors when the phase shifter is set to 10.000 mm gap. Measure the capacitive sensor reference piece before and after the phase shifter measurement. Place the data in the final results folder.

(b) Using the stretched wire, measure the background subtracted field integrals in the good field region. Perform stretched wire scans and calculate the first and second field integrals of $B_x$ and $B_y$. Use 0.5 mm wire motions for the measurements. Measure from $x = -2$ mm to $x = +2$ mm in 1 mm steps with $y = 0$. Measure from $y = -1$ mm to $y = +1$ mm in 0.5 mm steps with $x = 0$. Repeat this at gaps of 10, 12, 15, 20, 25, 30, 35, 100 mm. Place the data in the final results folder.

(c) Using the stretched wire, measure the background subtracted field integrals on the phase shifter axis. Perform stretched wire scans and compute the first and second field integrals of $B_x$ and $B_y$. Measure at $x = 0$, $y = 0$. Measure at gaps from 10 mm to 30 mm in 2 mm steps, then at gaps of 35, 40, 50, 60, 70, 80, 90, 100 mm. Place the data in the final results folder.

(d) Make files containing data for spline fits to be used by the control system to operate the phase shifter. The required files provide data for $I_1x$ vs gap, $I_1y$ vs gap, $I_2x$ vs gap, and $I_2y$ vs gap. $I_1x$ refers to the first integral of the $B_x$ field, $I_2x$ refers to the second integral, etc. The background field integrals must be subtracted from the field integrals in these files. Place these files in the final results folder.

(e) Measure the phase integrals in the good field region. Perform Hall probe scans and calculate the phase integral. Measure from $x = -1$ mm to $x = +1$ mm in 0.5 mm steps with $y = 0$. Measure from $y = -1$ mm to $y = +1$ mm in 0.5 mm steps with $x = 0$. Repeat this at gaps of 10, 12, 15, 20, 25, 30, 35, 100 mm. Place the data in the final results folder.

(f) Measure the phase integrals on the phase shifter axis. Perform Hall probe scans and compute the phase integral. Measure at $x = 0$, $y = 0$. Measure at gaps from 10 mm to 35 mm in 1 mm steps, then at gaps of 40, 45, 50, 55, 60, 70, 80, 90, 100 mm, and finally while closing the gap, measure at gaps from 35 mm to 10 mm in 1 mm steps. Place the data in the final results folder.

(g) Make files containing data for spline fits to be used by the control system to operate the phase shifter. The required file provides data for phase integral vs gap. Place these files in the final results folder.

(h) Fiducialize the phase shifter. Measure the fiducialization magnet with the Hall probe. Make a file with the magnetic center position for use by the alignment crew. Have an alignment crew measure all tooling ball positions relative to the
Hall probe measurement line. Place the fiducialization data in the final results folder.

(i) Place all phase shifter operating parameters, such as encoder offsets, in a file in the final results folder. (All operating parameters must also be included in each measurement file.)

6 Measurement Results

All raw data and analysis results will be available from the SLAC web site. The data will be stored in a directory structure as shown in Figure 2. The top level directory is "Magdata," followed by "LCLS-II-HE," followed by the magnet type "Phase Shifter." The "Phase Shifter" directory contains a "Background" directory with the stretched wire background field measurements which apply to all the phase shifters. In the "Phase Shifter" directory, there is a folder for each phase shifter named by the serial number. For each phase shifter, "Dataset" directories are made. When the phase shifter comes back for multiple measurements over time, each set of measurements goes into a new dataset. Within each dataset, the "Tuning," "Fiducialization," and "Final Results" folders are created.

After any setup or tuning runs are complete, a special set of final measurement runs is made. The results from these runs will go into a Final Results folder. The contents of the Final Results folder are shown in Figure 3.

For the Hall probe scans in the phase shifter, each measurement and its analysis results will go into a folder whose name is determined by the measurement number, the gap, and the x and y probe positions for the measurement. The fixed width format is "nnngapnnn.nnnxsnn.nnysnn.nn," where "s" represents a sign, "." represents a decimal point, and "n" is a decimal digit. The initial "nnn" is used to give the measurement number. The gap and probe positions are in millimeters. All data files will be text files. All Hall probe measurement data files will be called "zscan.dat." In this way the analysis programs can be more easily automated so the contents of a folder are known in advance. Analysis results will be in both text files and either PostScript plot files or PDF plot files.

For stretched wire measurements, a similar scheme to the Hall probe measurements is used. A run folder contains multiple measurements. Each measurement produces data files with format "nnngapnnn.nnnxsnn.nnysnn.nn_qqq_tt." The first part of the data file name, up to the first underscore, contains the measurement number, the gap, and the x and y wire position, using the same format as the Hall probe scans. After the first underscore, "qqq" describes the quantity being measured and will be either "i1x," "i2x," "i1y," or "i2y" for the first or second field integrals of \( B_x \) or \( B_y \). The "tt" refers to a file type descriptor. Summaries of the field integral measurements are provided in a file called "integrals_summary.txt."

Measurements of the phase shifter gap independent of the linear encoder go in the "Gap Measurements" folder. Different types of measurements may be made, for instance using capacitive sensors or a CMM. Results from each type of measurement go into a folder named by measurement type.

The final report giving the positions of all the tooling balls on the phase shifter relative to the Hall probe axis will be placed in the "Fiducialization" folder.
The “Controls Data” folder contains files needed to operate the phase shifter. Each file has the serial number both in the contents of the file and in the file name. The Controls group will put the contents of these files into their database. The files contain the phase shifter parameters used during testing, and a set of data for spline fits relating the phase integral and the field integrals to the phase shifter gap.

7 Summary

SLAC will perform tuning and calibration measurements for a final data set on the LCLS-II-HE phase shifters. Hall probe measurements will be used to determine the phase integral and the field integrals both on the phase shifter axis and within the good field region. The Earth’s field will be measured outside the phase shifter and subtracted from measurements in the phase shifter. A calibration will be performed to determine the temperature dependence of the phase integral. A transportation test to the tunnel will also be performed.
Figure 2: Directory structure for saving the phase shifter measurement data.
Figure 3: Contents of the Final Results folder.