Temperature Calibration Of The LCLS-II-HE Undulators And Phase Shifters

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Abstract

Temperature calibrations were performed on the LCLS-II-HE SXR undulators and phase shifters. The temperature was varied from 19 deg C to 21 deg C in 0.5 deg C steps. Measurements over the entire gap range of each device were made. A temperature coefficient for each device was calculated as a function of gap and files for spline fits were generated to account for the gap dependence of the temperature coefficient.

1 Introduction[1]

The temperature dependence of the LCLS-II-HE SXR undulators and phase shifters was measured, and the results of this calibration are presented in this note. One undulator and one phase shifter were used for the calibration. We assume the calibration applies to all LCLS-II-HE undulators and phase shifters because of the similarity of the devices. The undulator used was HE-SXU-000, and the phase shifter used was HE-SXPS-000. Both devices were first articles. The calibrations were required before the production undulators and phase shifters arrived because production devices will be installed in the existing LCLS-II SXR beam line as they are calibrated.

The procedure for the LCLS-II-HE temperature calibrations was very similar to the procedure used for the LCLS-II undulator and phase shifter temperature calibrations.[2,3] Measurements were made at 20.0, 19.0, 19.5, 20.5, and 21.0 deg C in that order. A final measurement at 20.0 deg C was planned but was not made due to the long laboratory shutdown after the 2022 electrical accident. During the shutdown, the laboratory air conditioner failed causing a temperature excursion which necessitated recalibrating the undulator. To make up for the final 20.0 deg C data point, measurements from previous datasets at 20.0 deg C are included in this analysis. At each temperature, the Hall probes were calibrated and the bench alignment was checked. At each temperature, a full set of measurements at many gaps was performed. Temperature coefficients $\frac{1}{K}\frac{dK}{dT}$ and $\frac{1}{PI}\frac{dPI}{dT}$ were determined.

[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 and Y. Levashov, "Temperature Dependence Of The LCLS-II Undulators And Phase Shifters", LCLS-TN-20-1, April, 2020.

[3] Z. Wolf and Y. Levashov, "Temperature Calibration Of The LCLS-II Undulators And Phase Shifters", LCLS-TN-21-5, May, 2021.

2 Accuracy Requirements

2.1 Requirements On The K Value And Phase Integral

The accuracy requirements of the temperature coefficients come from the accuracy requirements on the K value and phase integral. Other undulator and phase shifter requirements do not limit the temperature coefficient accuracy requirements. For instance, quantities like field integrals and phase errors have little temperature dependence. The phase matching is temperature dependent, but the correction is derived from the K value. The LCLS-II-HE undulator and phase shifter requirements come from a Physics Requirements Document.[4] The temperature dependent requirements of interest are:

1. The HE-SXR undulator K value must be set to $\Delta K/K < \pm 5.5 \times 10^{-4}$ at all gap settings and all temperatures in the tunnel.
2. The phase change of the HE-SXR phase shifter must be accurate to $\pm 5.8°$ at all operational gap settings and temperatures.

2.2 Requirements On The Temperature Coefficient

The temperature dependence of the undulators and phase shifters comes primarily from the temperature dependence of the permanent magnet material used to construct the devices.[5] If this was the only source of temperature dependence, the temperature coefficient would be a constant, independent of gap. Secondary effects make the temperature coefficients gap dependent, but typically the gap dependence is small. We wish to understand whether a single temperature coefficient can be used or whether a spline fit to the gap dependence must be used.

From the requirements on the K values and the phase integrals, we wish to establish a conservative limit on the accuracy required for the temperature coefficients. For the undulators, the temperature is measured in the tunnel and compared to the temperature when the undulator was calibrated, and then the temperature coefficient is used to correct the K value for the given gap setting. The process is as follows. The change in K value compared to the MMF measurement at a given gap setting is given by

$$\Delta K = \Gamma_u K_m (T_t - T_m) \tag{1}$$

where Γ_u is the temperature coefficient derived in this note

$$\Gamma_u = (1/K) dK/dT \tag{2}$$

and K_m is the K value measured in the MMF at the given gap and at temperature T_m. The K value in the tunnel is then

$$K_t = K_m + \Delta K \tag{3}$$

We wish the error on the K value in the tunnel to be less than $\delta K_t/K_t < 1 \times 10^{-4}$ due to the temperature correction. If a single temperature coefficient at all gaps is used instead of a gap dependent correction, the error on K_t from the temperature coefficient, δK_t, is given by

$$\begin{aligned} \delta K_t &= \delta(\Delta K) & (4)\\ &= \delta\Gamma_u K_m (T_t - T_m) & (5) \end{aligned}$$

[4] D. Cesar et al., "LCLS-II-HE SXR Undulator System", LCLS-II-HE Physics Requirements Document LCLSII–HE-1.3-PR-0049-R2.

[5] Z. Wolf and Y. Levashov, "Temperature Dependence Of The LCLS-II Undulators And Phase Shifters", LCLS-TN-20-1, April, 2020.

To lowest order, K_m can be replaced by K_t and

$$\delta K_t/K_t = \delta\Gamma_u\,(T_t - T_m) \tag{6}$$

For $\delta K_t/K_t < 1 \times 10^{-4}$,

$$\delta\Gamma_u\,(T_t - T_m) < 1 \times 10^{-4} \tag{7}$$

The tunnel temperature varies between 19 deg C and 21 deg C, and the MMF temperature is 20 deg C. The maximum difference in temperature between the tunnel and the MMF is 1 deg C.

$$|T_t - T_m| < 1 \text{ deg C} \tag{8}$$

This sets a limit on $\delta\Gamma_u$,

$$\delta\Gamma_u < 1 \times 10^{-4} \text{ 1/deg C} \tag{9}$$

In summary, if the temperature coefficient varies by less than 1×10^{-4} 1/deg C over the undulator gap range, we can use a constant value for the temperature correction rather than a spline fit of temperature coefficient as a function of gap.

The maximum error on the phase shifter temperature coefficient is calculated in a similar way. For the phase integral tolerance, however, the error is given in terms of phase and not in terms of the fractional change in phase integral. We must start by relating the error in phase to the error in phase integral. The phase of a phase shifter is related to the phase integral by

$$\phi = 2\pi \frac{\left(\frac{q}{mc}\right)^2 PI}{\lambda_u \left(1 + \frac{1}{2}K^2\right)} \tag{10}$$

where PI is the phase integral of the phase shifter. The error on the phase is related to the error on the phase integral by

$$\delta\phi = 2\pi \frac{\left(\frac{q}{mc}\right)^2}{\lambda_u \left(1 + \frac{1}{2}K^2\right)} \delta PI \tag{11}$$

Using the maximum error on the phase and the minimum undulator K value, we get the following limits on the maximum phase integral error:

$$\delta PI_{\max} < 5.61 \text{ T}^2\text{mm}^3 \tag{12}$$

We wish to use at most one third of this error for the temperature correction. In this case we set the limits on the phase integral error from the temperature correction to be

$$\delta PI < 1.87 \text{ T}^2\text{mm}^3 \tag{13}$$

The phase integral changes with temperature according to

$$\Delta PI = \Gamma_{ps} PI_m\,(T_t - T_m) \tag{14}$$

where Γ_{ps} is the temperature coefficient for the phase shifter derived in this note

$$\Gamma_{ps} = (1/PI)dPI/dT \tag{15}$$

and PI_m is the phase integral measured in the MMF at the given gap and at temperature T_m. The PI value in the tunnel is then

$$PI_t = PI_m + \Delta PI \tag{16}$$

The error on the phase integral in the tunnel due to using a constant temperature coefficient rather than including the gap dependence is

$$\delta PI_t = \delta(\Delta PI) \tag{17}$$

$$= \delta\Gamma_{ps} PI_m\,(T_t - T_m) \tag{18}$$

To lowest order PI_m can be replaced by PI_t, and

$$\delta\Gamma_{ps} = \frac{\delta PI_t}{PI_t} \frac{1}{(T_t - T_m)} \tag{19}$$

The smallest value of $\delta\Gamma_{ps}$ occurs when PI_t is the maximum value in the operating range and $(T_t - T_m)$ is the maximum value in the tunnel, which is 1 deg C as noted above.

$$\delta\Gamma_{ps} < \frac{\delta PI_t}{\max(PI_t)} \frac{1}{\max(T_t - T_m)} \tag{20}$$

From the Physics Requirements Document, the maximum phase integral in the operating range is

$$\max(PI_t) = 9500 \text{ T}^2\text{mm}^3 \tag{21}$$

Inserting these values in the formula for $\delta\Gamma_{ps}$, we have

$$\delta\Gamma_{ps} < \frac{1.87 \text{ T}^2\text{mm}^3}{9500 \text{ T}^2\text{mm}^3} \cdot \frac{1}{1 \text{ deg C}} \tag{22}$$

$$< 1.97 \times 10^{-4} \text{ 1/deg C} \tag{23}$$

If the variation in temperature coefficient with gap is smaller than this values, a constant temperature coefficient can be used.

3 Analysis Of The Measurements

3.1 HE-SXR Undulators

The temperature of the HE-SXR undulator during the test is shown in figure 1. The temperatures are constant and at the expected values of 20.0, 19.0, 19.5, 20.5, and 21.0 deg C. Since a final 20.0 deg C measurement was not possible, measurements from two previous datasets (DS1 and DS2 in the plot legend) taken at 20.0 deg C are included in the analysis. The temperature calibration was done in dataset 3.

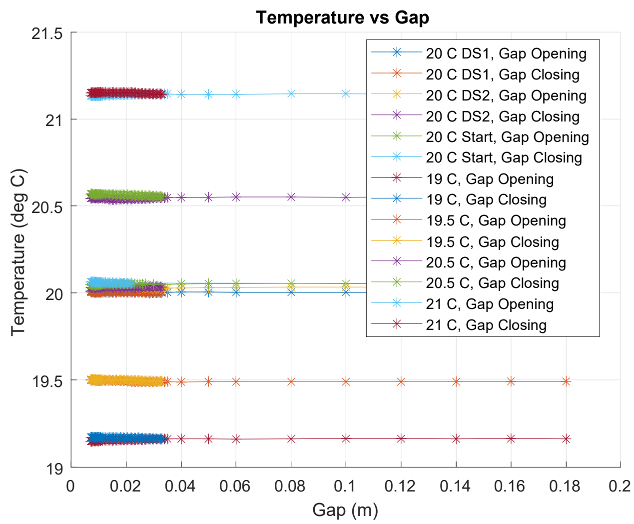

Figure 1: Temperature of the HE-SXR undulator during the test.

At a fixed gap of 10 mm set as the gap is opening, the K value as a function of temperature is shown in figure 2. The K values vary linearly with temperature over the small temperature range. K as a function of temperature at alternate gaps for clarity as the gap is opening is shown in figure 3. The plot illustrates that K varies linearly with temperature over the small temperature range at all gaps.

At each gap, the slope of the fitted line to K vs temperature gives dK/dT. This quantity could be used for the temperature corrections. The value of dK/dT as a function of gap is shown in figure 4. Values are given for both the gap opening and for the gap closing. The median values between the gap opening and the gap closing are used to generate points for a spline fit. The spline points and the spline fit are also shown in the figure. The spline points are output in a data file which can be used for temperature corrections. Note that dK/dT varies significantly over the gap range, whereas the temperature coefficient given below has less variation. At small gap, the dK/dT values deviate from the rest of the curve. This is due to a small saturation of the steel poles in the undulator.

Dividing the slope of K vs temperature by the average K value gives the calibration constant $1/K\ dK/dT$. The calibration constant as a function of gap is plotted in figure 5. Values for both the gap opening and gap closing are shown. The mean values between the gap opening and gap closing are used to make spline points. The spline points along with the spline fit are also shown.

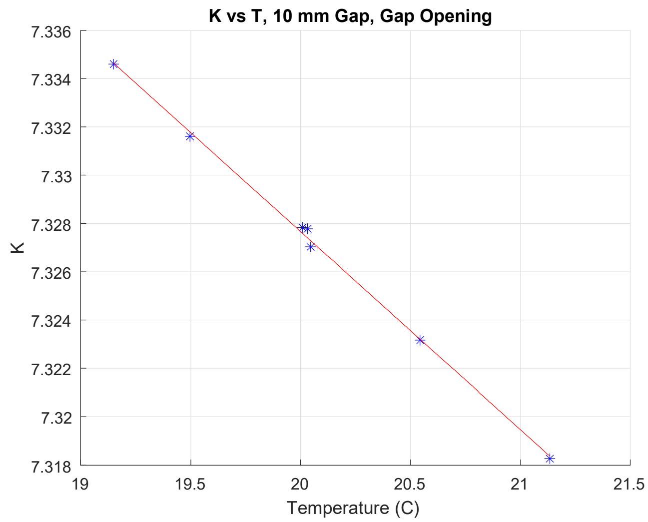

Figure 2: HE-SXR undulator K as a function of temperature at 10 mm gap.

The spline points are output in a data file. The average over all gaps is

$$\frac{1}{K}\frac{dK}{dT} = -1.08 \times 10^{-3} \text{ 1/deg C} \tag{24}$$

The variation of the curve from the average value is 0.6×10^{-4} 1/deg C. This is below the tolerance of 1×10^{-4} 1/deg C, so the average value of the temperature coefficient can be used instead of the spline fit.

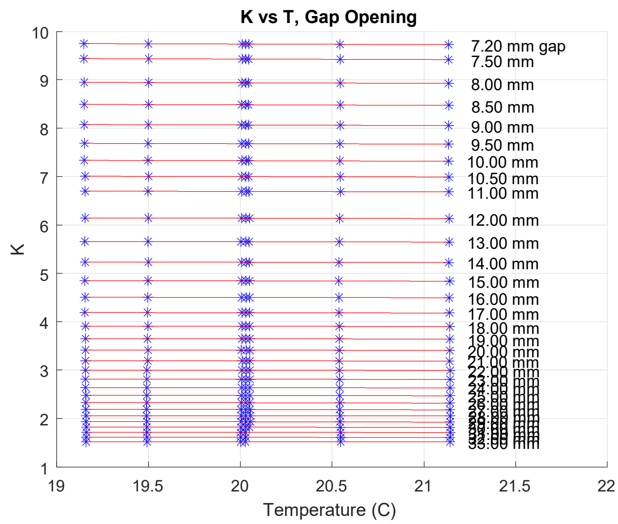

Figure 3: HE-SXR undulator K as a function of temperature at all gaps as the gap is opening.

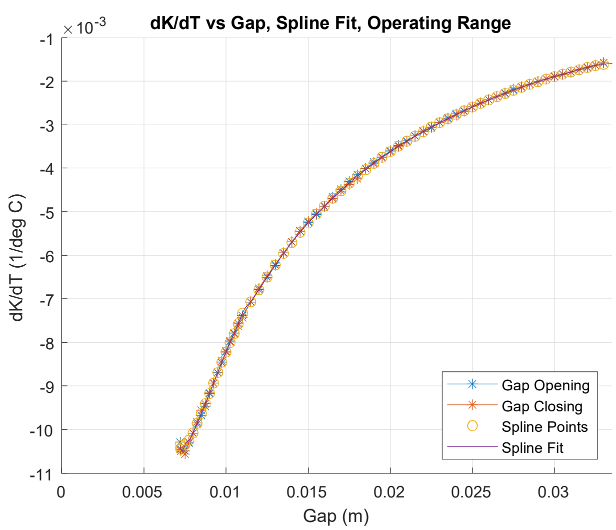

Figure 4: HE-SXR undulator dK/dT as a function of gap. Values for both the gap opening and the gap closing are shown. Median values are used to generate points for a spline fit. The points for the fit and the fit itself are also shown.

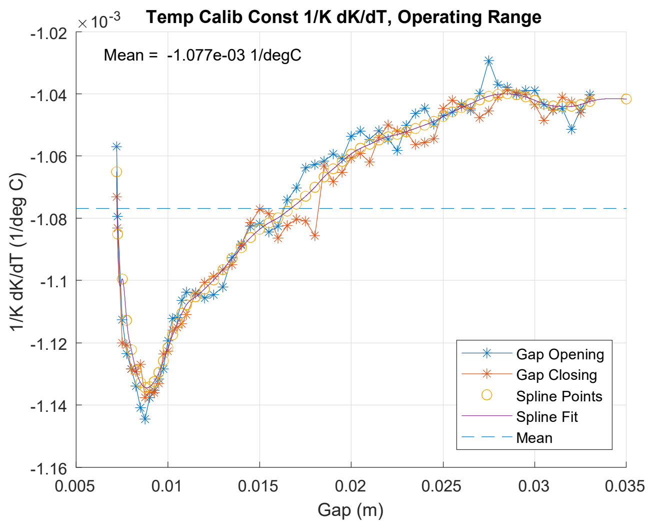

Figure 5: HE-SXR undulator calibration constant $1/K\ dK/dT$ as a function of gap.

3.2 HE-SXR Phase Shifters

The temperature of the HE-SXR phase shifter during the test is shown in figure 6. The temperatures are constant but are slightly higher than the expected values of 20.0, 19.0, 19.5, 20.5, and 21.0 deg C due to the heating of the bottom jaw by the encoder read head. Because the final 20.0 deg C measurement could not be made, measurements from the phase shifter calibration at 20.0 deg C are included in the analysis. These points are from dataset 1 and are indicated by DS1 in the legend of the plot.

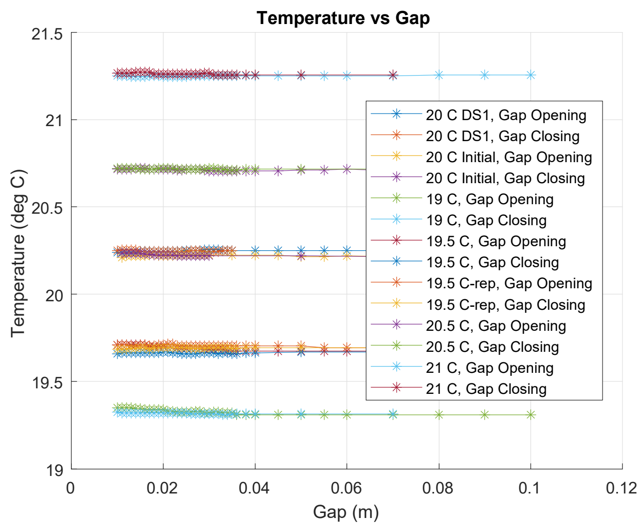

Figure 6: Temperature of the HE-SXR phase shifter during the test.

At a fixed gap of 15 mm set as the gap is opening, the PI value as a function of temperature is shown in figure 7. The PI values vary linearly with temperature over the small temperature range. PI as a function of temperature at all gaps as the gap is opening is shown in figure 8. The plot illustrates that PI varies linearly with temperature over the small temperature range at all gaps.

At each gap, the slope of the fitted line to PI vs temperature gives dPI/dT. This quantity could be used for the temperature corrections. The value of dPI/dT as a function of gap is shown in figure 9. Values are given for both the gap opening and for the gap closing. The median values between the gap opening and the gap closing are used to generate points for a spline fit. The spline points and the spline fit are also shown in the figure. The spline points are output in a data file which can be used for temperature corrections. Note that dPI/dT varies significantly over the gap range, whereas the temperature coefficient given below has less variation.

Dividing the slope of PI vs temperature by the average PI value gives the calibration constant $1/PI\ dPI/dT$. The calibration constant as a function of gap is plotted in figure 10. Values for both the gap opening and gap closing are shown. The difference is due to mechanical hysteresis in the jaw angle due to the large magnetic forces. The mean values between the gap opening and gap closing are used to make spline points. The spline points along with the spline fit are also shown. The spline points are output in a data file. The average calibration constant over all gaps is

$$\frac{1}{PI}\frac{dPI}{dT} = -1.88 \times 10^{-3}\ 1/\text{deg C} \tag{25}$$

The calibration constant varies from the mean value by approximately 1.0×10^{-4} 1/deg C. This is

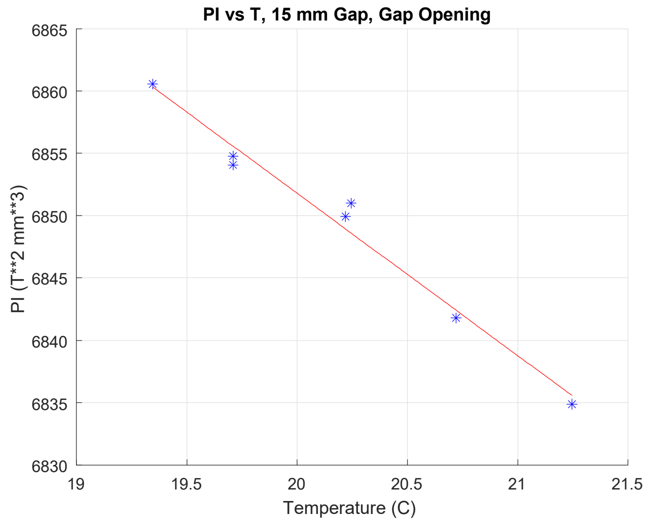

Figure 7: HE-SXR phase shifter PI as a function of temperature at 15 mm gap.

less than the limit of 1.97×10^{-4} 1/deg C given in the requirements section. The constant average value of the calibration constant can be used to correct the PI values of the SXR phase shifters.

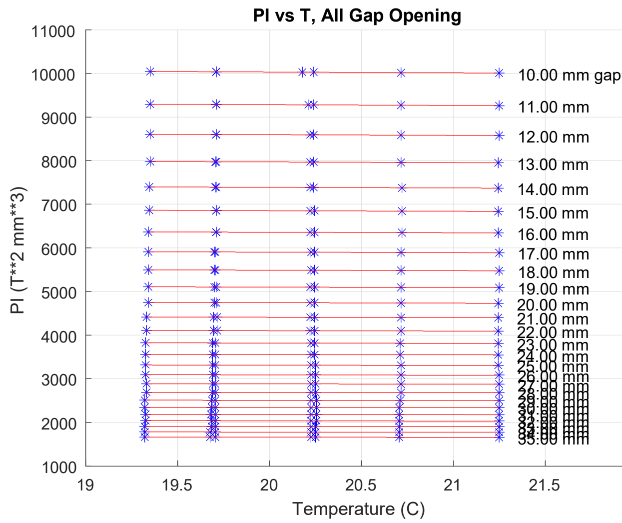

Figure 8: HE-SXR phase shifter PI as a function of temperature at all gaps as the gap is opening.

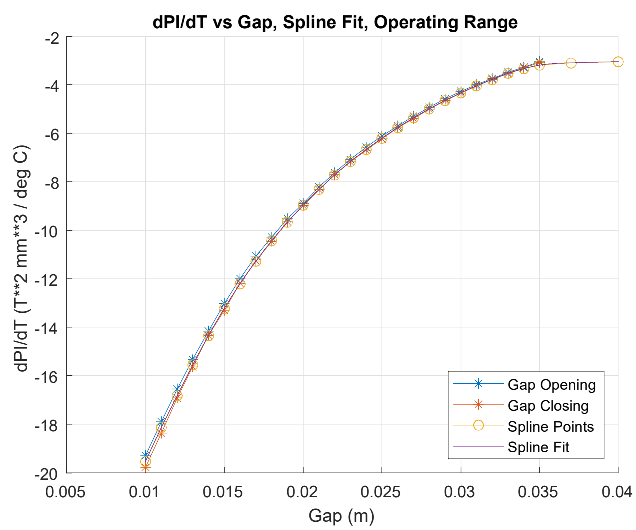

Figure 9: HE-SXR phase shifter dPI/dT as a function of gap. Values for both the gap opening and the gap closing are shown. Median values are used to generate points for a spline fit. The points for the fit and the fit itself are also shown.

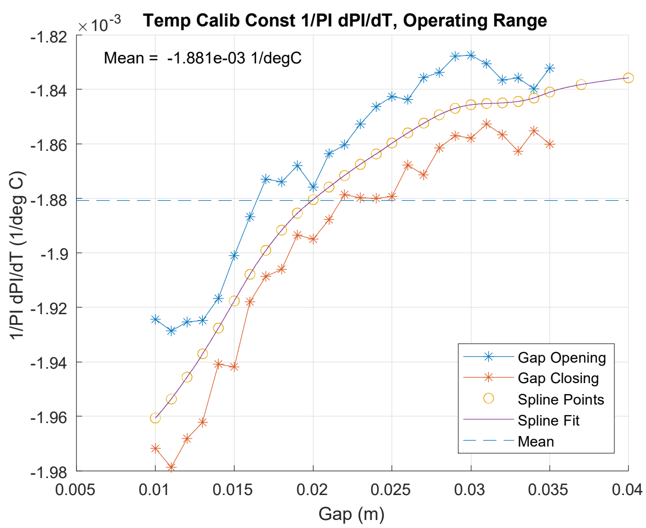

Figure 10: HE-SXR phase shifter calibration constant $1/PI\ dPI/dT$ as a function of gap.

4 Summary

Temperature corrections are required for LCLS-II undulators and phase shifters which are operated in the tunnel at different temperatures than their calibrations were performed at. The temperature corrections can be done with a single calibration factor for the undulator K values and phase shifter phase integrals. The temperature calibration factor was obtained on one HE-SXR undulator and one HE-SXR phase shifter, but is assumed to be the same for all of each type of device. The mean temperature calibration factors obtained from the measurements detailed in this note are:

Device	Calibration Factor
HE-SXR Undulator	$(1/K)dK/dT = -1.08 \times 10^{-3}$ 1/deg C
HE-SXR Phase Shifter	$(1/PI)dPI/dT = -1.88 \times 10^{-3}$ 1/deg C

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