Temperature Calibration Of The LCLS-II Undulators And Phase Shifters

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Abstract

This note is a continuation of an effort to understand and find a calibration for the temperature dependence of the LCLS-II undulators and phase shifters. For the present work, the LCLS-II SXR and HXR undulators and phase shifters were calibrated at temperatures 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 SXR and HXR undulators and phase shifters was studied in a previous note[2]. In the previous note, a detailed theoretical analysis was performed, but limited temperature measurements were made due to time constraints. This note is a continuation of the previous effort. A repeat of the theoretical analysis is not performed, but an extensive set of measurements is presented. The measurements are used to calculate the temperature coefficient of each device as a function of gap. Spline files of the temperature coefficients as a function of gap were generated and can be used for temperature corrections in the tunnel.

The primary source of changes due to temperature in the undulator K value and the phase shifter phase integral is the permanent magnet material. The NdFeB magnets in the SXR undulators are of type VACODYM 956 DTP and have a remnant field temperature coefficient of[3] $(1/B_r)dB_r/dT \simeq -1.0 \times 10^{-3}$ 1/deg C. The NdFeB magnets in the HXR undulators are of type Neorem 776T and have a remnant field temperature coefficient of[4] $(1/B_r)dB_r/dT \simeq -0.8 \times 10^{-3}$ 1/deg C. The NdFeB magnets in the SXR and HXR phase shifters are of type VACODYM 983 TP and have a remnant field temperature coefficient of[5] $(1/B_r)dB_r/dT \simeq -0.9 \times 10^{-3}$ 1/deg C. We expect the SXR undulators to have a temperature coefficient of $(1/K)dK/dT \simeq -1.0 \times 10^{-3}$ 1/deg C, and the HXR undulators to have a temperature coefficient of $(1/K)dK/dT \simeq -0.8 \times 10^{-3}$ 1/deg C. Because of the quadratic dependence on field, we expect both the SXR and HXR phase shifters to have a temperature coefficient of $(1/PI)dPI/dT \simeq -1.8 \times 10^{-3}$ 1/deg C. Secondary effects such as saturation of steel poles, changes of the remnant field temperature coefficients with batch, changes of

[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] Value from www.vacuumschmelze.com.

[4] Neorem data sheet courtesy of Diego Arbelaez, LBNL.

[5] Value from www.vacuumschmelze.com.

the gap with temperature, changes in permeability with temperature, and changes in device length with temperature will modify these values and give a gap dependence to the temperature coefficient.

Measurements were made at 20.0, 19.0, 19.5, 20.5, 21.0, and 20.0 deg C in that order. 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. The SXR undulator used for the test was SXU-021. The HXR undulator was HXU-000. The SXR phase shifter was SXPS-15081, and the HXR phase shifter was HXPS-16321. We assume that the calibration results from these devices apply to all undulators and phase shifters because of the similarity of the units.

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 undulator requirements come from a Physics Requirements Document[6]. The temperature dependent requirements of interest are:

1. The SXR undulator K value must be set to $\Delta K/K < \pm 3 \times 10^{-4}$ at all gap settings and all temperatures in the tunnel.

2. The HXR undulator K value must be set to $\Delta K/K < \pm 2.3 \times 10^{-4}$ at all gap settings and all temperatures in the tunnel.

The LCLS-II phase shifter requirements also come from a Physics Requirements Document[7]. The temperature dependent requirements are summarized below:

1. The phase change of the SXR phase shifter must be accurate to $\pm 5.8°$ at all operational gap settings and temperatures.

2. The phase change of the HXR phase shifter must be accurate to $\pm 2.9°$ at all operational gap settings and temperatures.

2.2 Requirements On The Temperature Coefficient

As noted in the introduction, 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. 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 SXR and HXR 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

[6] H. D. Nuhn et al., "Undulator System Requirements", LCLS-II Physics Requirements Document LCLSII-3.2-PR-0038-R3.

[7] H. D. Nuhn et al., "Undulator Phase Shifter", LCLS-II Physics Requirements Document LCLSII-3.2-PR-0105-R1.

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

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

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 for each undulator line, we get the following limits on the maximum phase integral error:

$$\begin{aligned} \delta PI_{\max} &< 3.23 \text{ T}^2\text{mm}^3 \text{ (SXPS)} & (12)\\ \delta PI_{\max} &< 0.67 \text{ T}^2\text{mm}^3 \text{ (HXPS)} & (13) \end{aligned}$$

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

$$\delta PI < 1.1\ \mathrm{T}^2\mathrm{mm}^3\ \text{(SXPS)} \tag{14}$$

$$\delta PI < 0.2\ \mathrm{T}^2\mathrm{mm}^3\ \text{(HXPS)} \tag{15}$$

The phase integral changes with temperature according to

$$\Delta PI = \Gamma_{ps} PI_m\,(T_t - T_m) \tag{16}$$

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

$$\Gamma_{ps} = (1/PI)dPI/dT \tag{17}$$

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

$$PI_t = PI_m + \Delta PI \tag{18}$$

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

$$\delta PI_t = \delta(\Delta PI) \tag{19}$$

$$= \delta\Gamma_{ps} PI_m\,(T_t - T_m) \tag{20}$$

To lowest order PI_m can be replaced by PI_t, and

$$\delta\Gamma_{ps} = \frac{\delta PI_t}{PI_t}\frac{1}{(T_t - T_m)} \tag{21}$$

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.

$$\delta\Gamma_{ps} < \frac{\delta PI_t}{\max(PI_t)}\frac{1}{\max(T_t - T_m)} \tag{22}$$

From the Physics Requirements Document[8], the maximum phase integrals in the operating range are

$$\max(PI_t) = 3814\ \mathrm{T}^2\mathrm{mm}^3\ \text{(SXR)} \tag{23}$$

$$= 490\ \mathrm{T}^2\mathrm{mm}^3\ \text{(HXR)} \tag{24}$$

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

$$\delta\Gamma_{ps} < \frac{1.1\ \mathrm{T}^2\mathrm{mm}^3}{3814\ \mathrm{T}^2\mathrm{mm}^3}\frac{1}{1\ \text{deg C}} \tag{25}$$

$$< 2.9\times10^{-4}\ 1/\text{deg C (SXR)} \tag{26}$$

For the HXR line, we have

$$\delta\Gamma_{ps} < \frac{0.2\ \mathrm{T}^2\mathrm{mm}^3}{490\ \mathrm{T}^2\mathrm{mm}^3}\frac{1}{1\ \text{deg C}} \tag{27}$$

$$< 4.1\times10^{-4}\ 1/\text{deg C (HXR)} \tag{28}$$

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

[8] H. D. Nuhn et al., "Undulator Phase Shifter", LCLS-II Physics Requirements Document LCLSII-3.2-PR-0105-R1.

3 Analysis Of The Measurements

3.1 SXR Undulators

The temperature of the 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, 21.0, and 20.0 deg C.

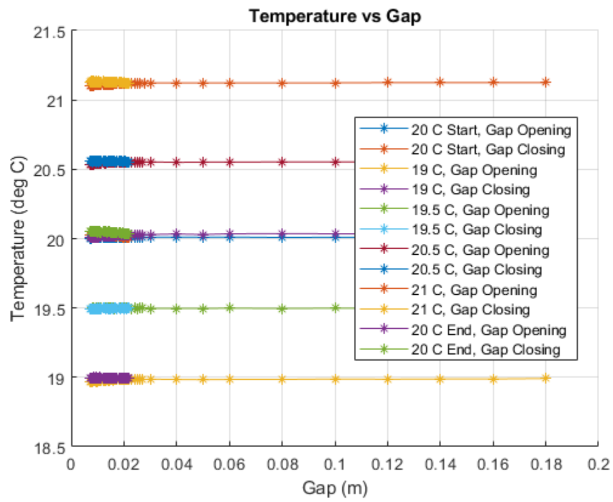

Figure 1: Temperature of the SXR undulator during the test.

At a fixed gap of 9 mm and 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. Note that the final K value at 20 deg C is lower than the initial value. This is a problem with SXU-021 that is under investigation, however, it does not have a significant effect on the fit to K vs temperature. K as a function of temperature at all gaps as the gap is opening is shown in figure 3. The small drift in K in the final 20 deg C measurements is evident. The fitted K value at 20 deg C was subtracted from all the measurements and the fit for each gap value. This was done so that all points would have comparable values on the same plot. 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 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. The spline points are output in a data file. The average over all gaps is

$$\frac{1}{K}\frac{dK}{dT} = -8.97 \times 10^{-4}\ 1/\text{deg C} \tag{29}$$

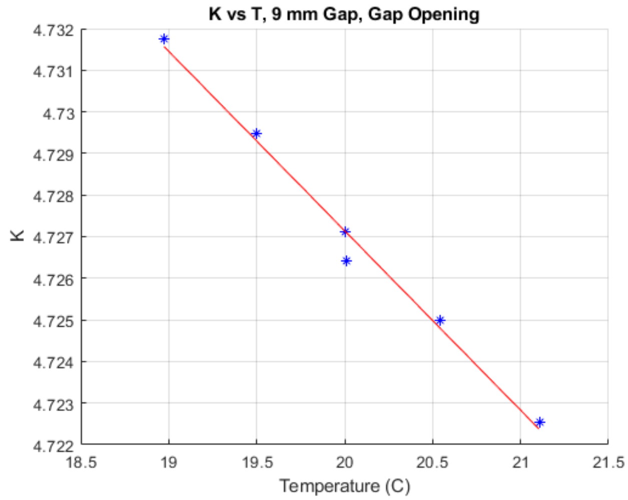

Figure 2: SXR undulator K as a function of temperature at 9 mm gap.

Because of the pole saturation, the calibration constant varies from the mean value by 2×10^{-4} 1/deg C at small gap. This is larger than the 1×10^{-4} 1/deg C limit set in the requirements section. The spline fit should be used to correct the K values of the SXR undulators.

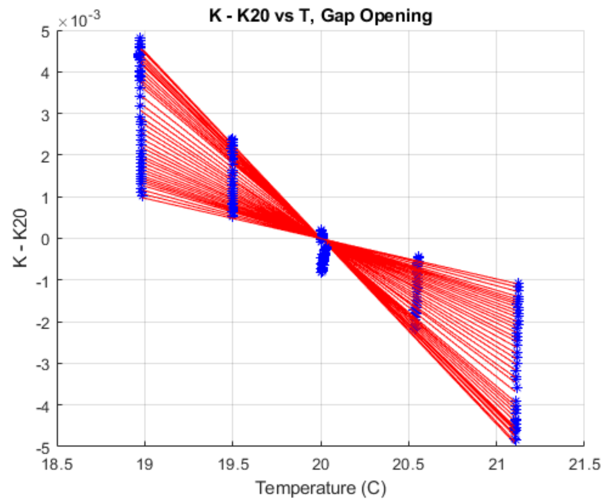

Figure 3: SXR undulator K as a function of temperature at all gaps as the gap is opening.

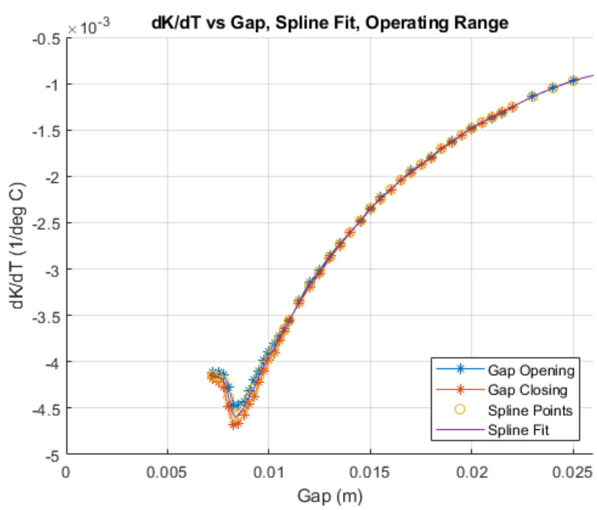

Figure 4: SXR undulator dK/dT as a function of gap. Values for both the gap opening and the gap closing are shown. Median values are used to generate points for a spline fit. The points for the fit and the fit itself are also shown.

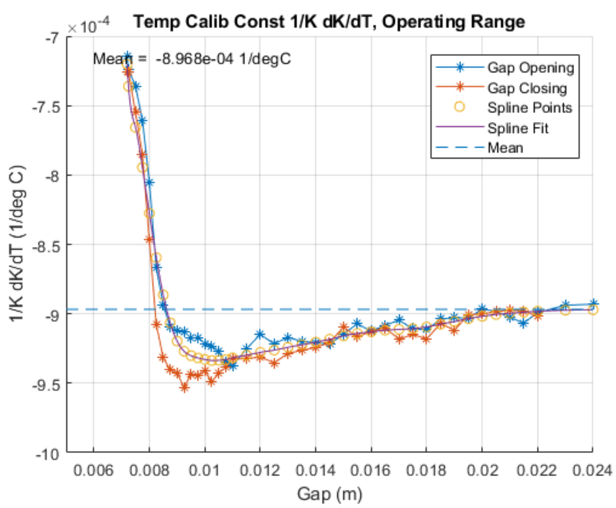

Figure 5: SXR undulator calibration constant $1/K\ dK/dT$ as a function of gap.

3.2 HXR Undulators

The temperature of the HXR undulator during the test is shown in figure 6. The temperatures are constant and near the expected values of 20.0, 19.0, 19.5, 20.5, 21.0, and 20.0 deg C.

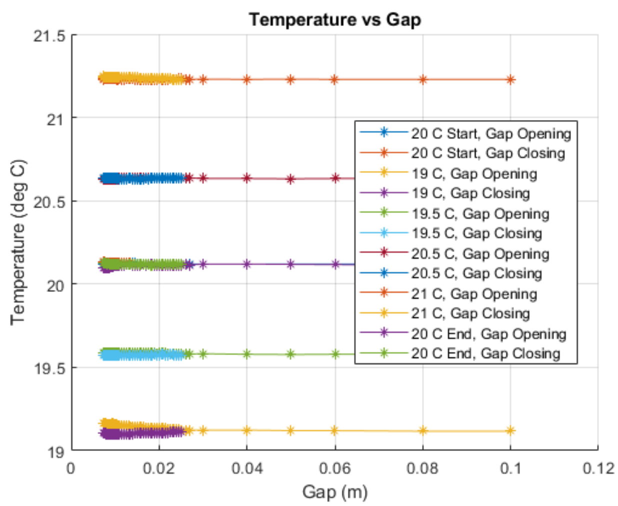

Figure 6: Temperature of the HXR undulator during the test.

At a fixed gap of 9 mm and as the gap is opening, the K value as a function of temperature is shown in figure 7. The K values vary linearly with temperature over the small temperature range. K as a function of temperature at all gaps as the gap is opening is shown in figure 8. The fitted K value at 20 deg C was subtracted from all the measurements and the fit for each gap value. This was done so that all points would have comparable values on the same plot. The plot illustrates that K varies linearly with temperature over the small temperature range at all gaps.

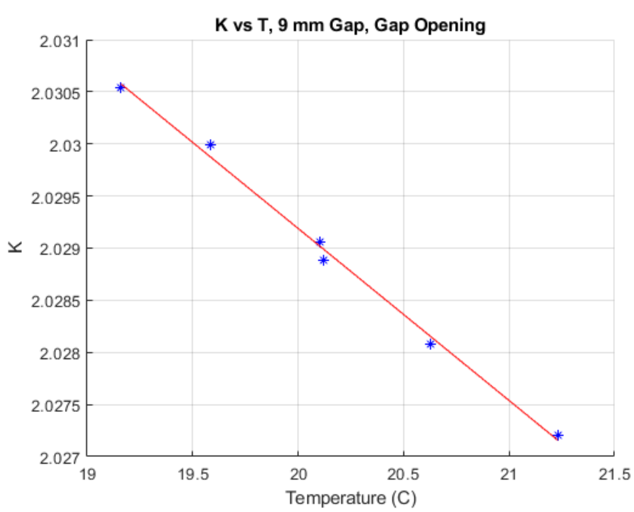

Figure 7: HXR undulator K as a function of temperature at 9 mm gap.

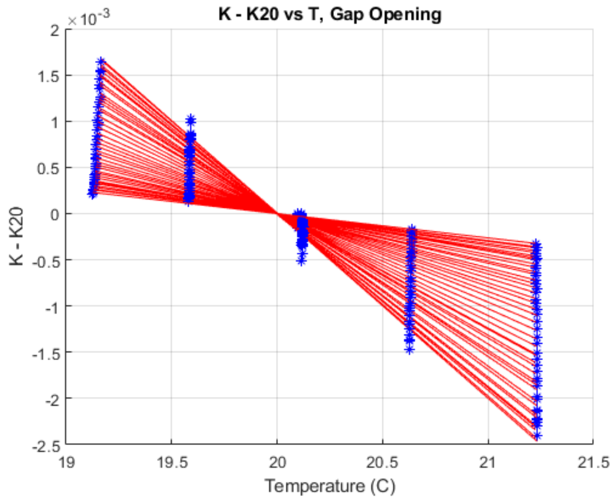

Figure 8: HXR undulator K as a function of temperature at all gaps as the gap is opening.

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 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 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 slightly from the rest of the curve, but the effect is much smaller than for the SXR undulators. This is due to 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 10. 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. The spline points are output in a data file. The average over all gaps is

$$\frac{1}{K}\frac{dK}{dT} = -7.97 \times 10^{-4}\ 1/\text{deg C} \tag{30}$$

Because of the pole saturation, the calibration constant varies from the mean value by approximately 1×10^{-4} 1/deg C at small gap. The spline fit should be used to correct the K values of the HXR undulators.

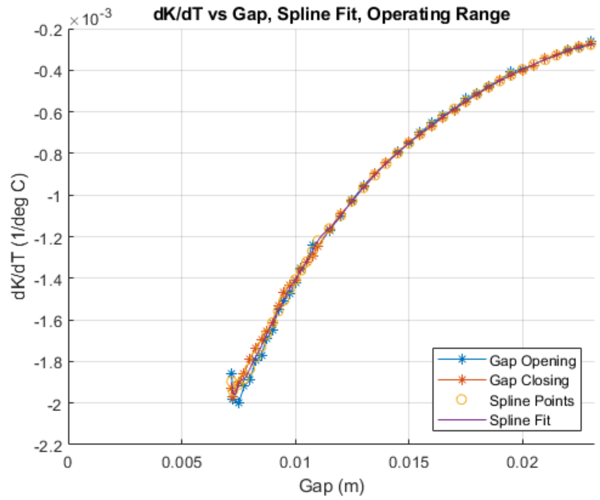

Figure 9: HXR undulator dK/dT as a function of gap. Values for both the gap opening and the gap closing are shown. Median values are used to generate points for a spline fit. The points for the fit and the fit itself are also shown.

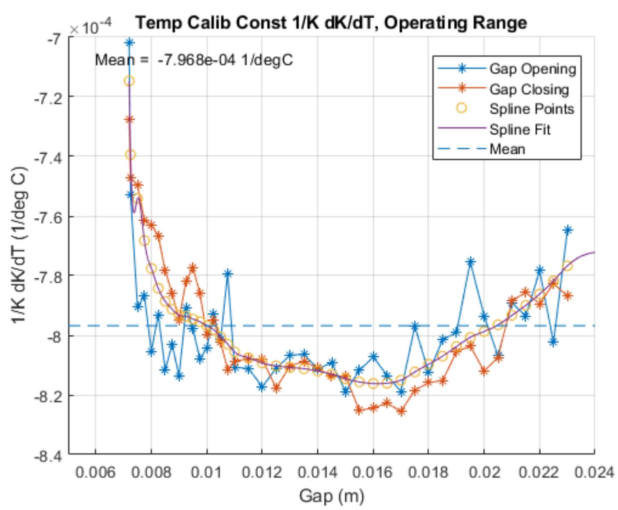

Figure 10: HXR undulator calibration constant $1/K\ dK/dT$ as a function of gap.

3.3 SXR Phase Shifters

The temperature of the SXR phase shifter during the test is shown in figure 11. The temperatures are constant but are slightly higher than the expected values of 20.0, 19.0, 19.5, 20.5, 21.0, and 20.0 deg C due to the heating of the bottom jaw by the encoder read head.

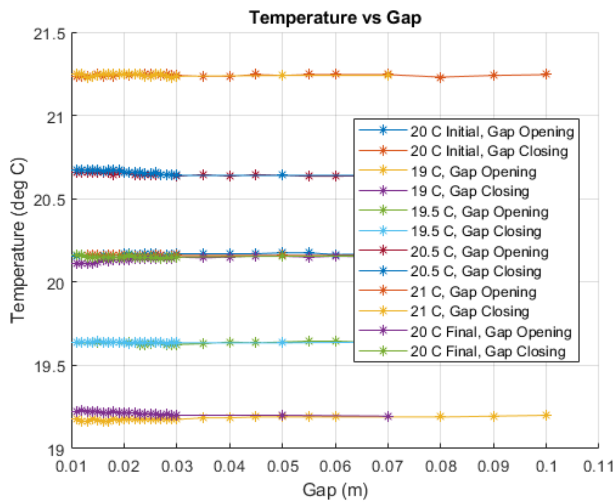

Figure 11: Temperature of the SXR phase shifter during the test.

At a fixed gap of 15 mm and as the gap is opening, the PI value as a function of temperature is shown in figure 12. 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 13. The fitted PI value at 20 deg C was subtracted from all the measurements and the fit for each gap value. This was done so that all points would have comparable values on the same plot. The plot illustrates that PI varies linearly with temperature over the small temperature range at all gaps.

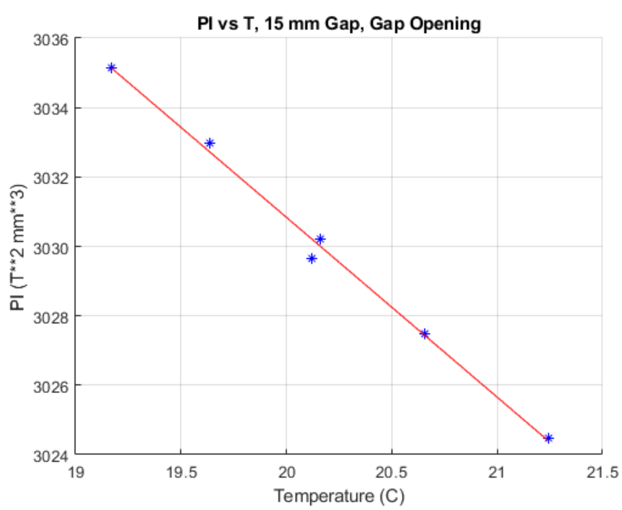

Figure 12: SXR phase shifter PI as a function of temperature at 15 mm gap.

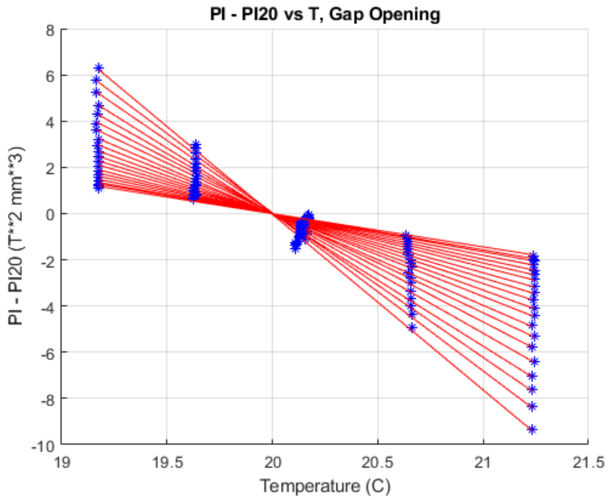

Figure 13: SXR phase shifter PI as a function of temperature at all gaps as the gap is opening.

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

$$\frac{1}{PI}\frac{dPI}{dT} = -1.68 \times 10^{-3} \ 1/\text{deg C} \tag{31}$$

The calibration constant varies from the mean value by approximately 0.8×10^{-4} 1/deg C. This is less than the limit of 2.9×10^{-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.

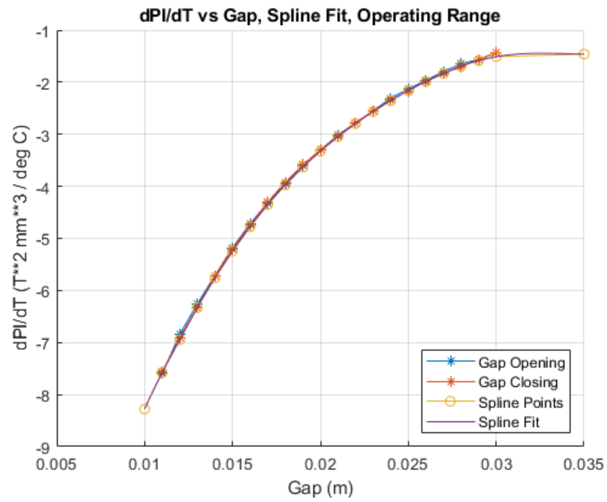

Figure 14: SXR phase shifter dPI/dT as a function of gap. Values for both the gap opening and the gap closing are shown. Median values are used to generate points for a spline fit. The points for the fit and the fit itself are also shown.

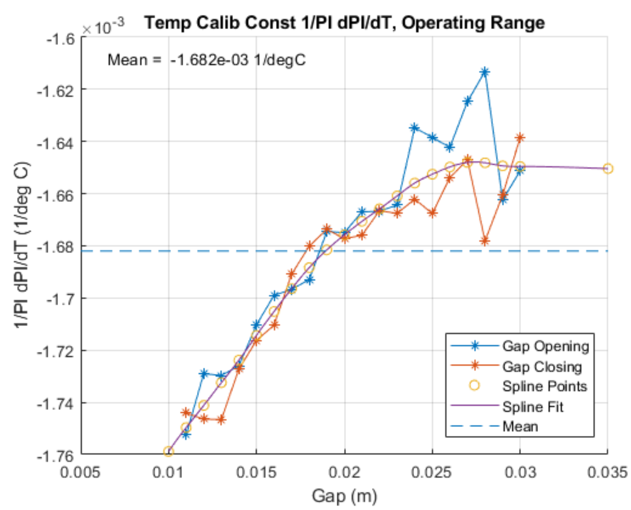

Figure 15: SXR phase shifter calibration constant $1/PI\ dPI/dT$ as a function of gap.

3.4 HXR Phase Shifters

The temperature of the HXR phase shifter during the test is shown in figure 16. The temperatures are generally constant but are about 0.6 deg C higher than the expected values of 20.0, 19.0, 19.5, 20.5, 21.0, and 20.0 deg C due to the heating of the bottom jaw by the encoder read head. The phase shifter was set to small gap before the start of the 19.5 deg C measurements. Air cooling was reduced, so the phase shifter started the test warmer than usual but then settled to an equilibrium temperature, as shown in the figure. Because a number of other points are used in the fit of the calibration constant, the effect of this temperature rise should be minimal.

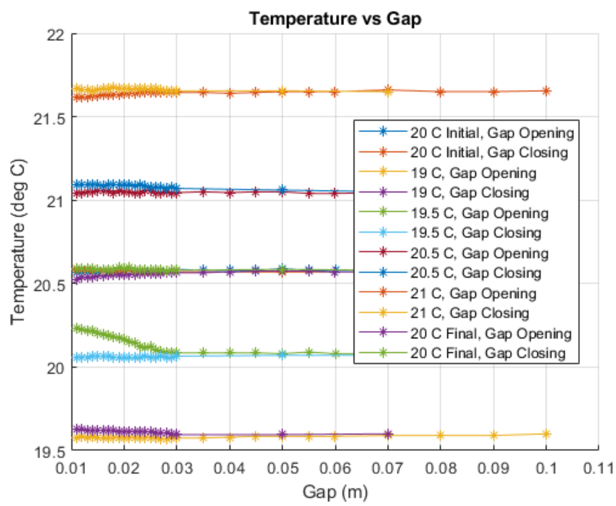

Figure 16: Temperature of the HXR phase shifter during the test.

At a fixed gap of 15 mm and as the gap is opening, the PI value as a function of temperature is shown in figure 17. 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 18. The fitted PI value at 20 deg C was subtracted from all the measurements and the fit for each gap value. This was done so that all points would have comparable values on the same plot. The plot illustrates that PI varies linearly with temperature over the small temperature range at all gaps. The temperature drift at nominal 19.5 deg C (actual 20.1 deg C) is evident in the plot.

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

$$\frac{1}{PI}\frac{dPI}{dT} = -1.51 \times 10^{-3}\ 1/\text{deg C} \tag{32}$$

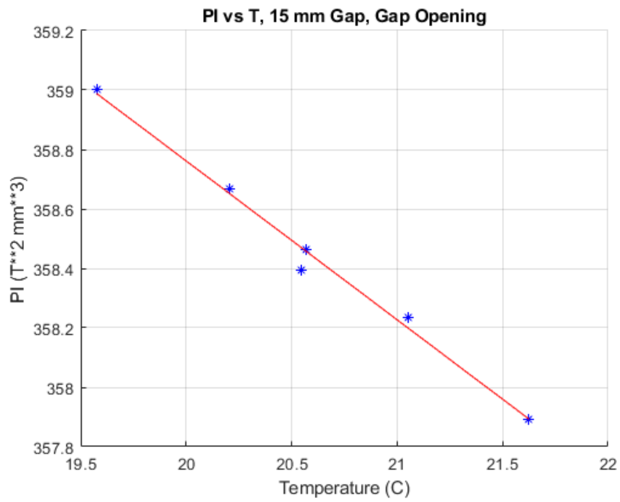

Figure 17: HXR phase shifter PI as a function of temperature at 15 mm gap.

The calibration constant varies from the mean value by approximately 0.9×10^{-4} 1/deg C. This is less than the limit of 4.1×10^{-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 HXR phase shifters.

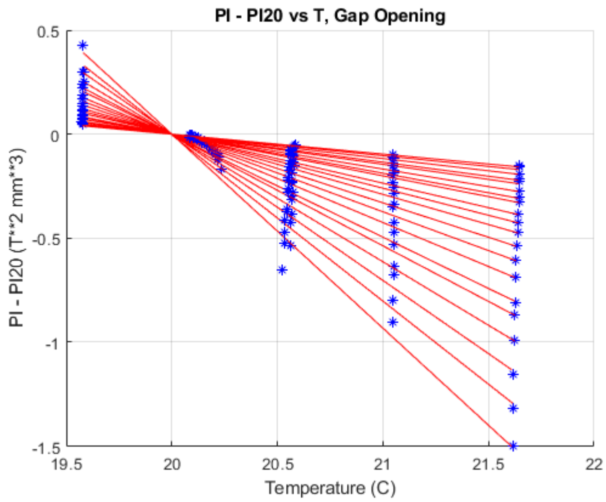

Figure 18: HXR phase shifter PI as a function of temperature at all gaps as the gap is opening.

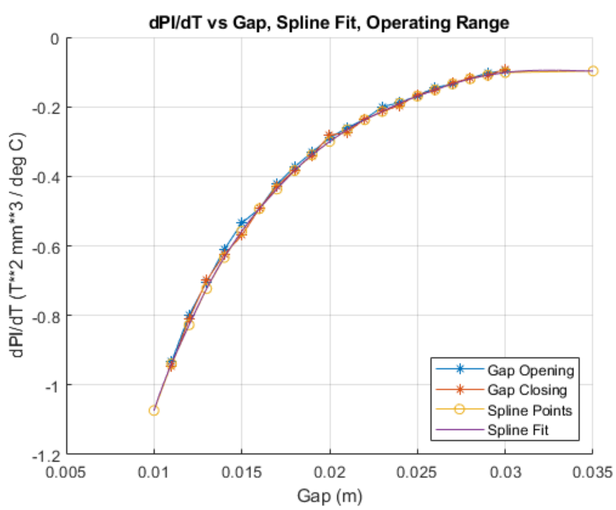

Figure 19: HXR phase shifter dPI/dT as a function of gap. Values for both the gap opening and the gap closing are shown. Median values are used to generate points for a spline fit. The points for the fit and the fit itself are also shown.

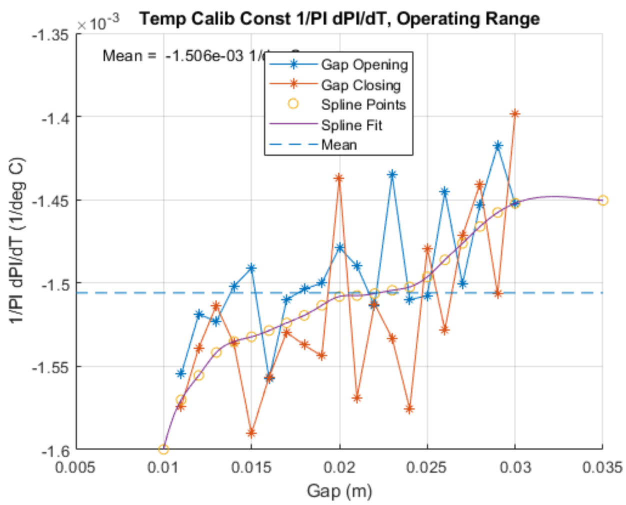

Figure 20: HXR phase shifter calibration constant $1/PI\ dPI/dT$ as a function of gap.

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 spline fit to the temperature calibration factor as a function of gap for the undulator K values and a single calibration factor for the phase shifter phase integrals. The temperature calibration factor was obtained on one each SXR undulator, HXR undulator, SXR phase shifter, and HXR 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
SXR Undulator	$(1/K)dK/dT = -8.97 \times 10^{-4}$ 1/deg C
HXR Undulator	$(1/K)dK/dT = -7.97 \times 10^{-4}$ 1/deg C
SXR Phase Shifter	$(1/PI)dPI/dT = -1.68 \times 10^{-3}$ 1/deg C
HXR Phase Shifter	$(1/PI)dPI/dT = -1.51 \times 10^{-3}$ 1/deg C

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