A Study Of The Effects Of LCLS Undulator Beam Pipe Heating Without Water Cooling

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Abstract

A study was made to determine the effects of LCLS undulator beam pipe heating if water cooling is not implemented. A particular focus was to see if the undulator K values could be corrected by measuring the temperature of the magnet keepers and adjusting the undulator gaps to correct for temperature. This approach appears feasible and this note documents the results of the tests.

1 Introduction[1]

When the repetition rate of the LCLS-II electron beam increases with the superconducting accelerator, increased power will be deposited in the undulator beam pipes. This power will heat the beam pipes, which in turn will heat the undulator magnets when the undulator gap is closed. Heating the magnets will change their strength, which will change the K value of the undulator. Previous studies determined a method to cool the beam pipes to the local ambient air temperature so that the undulator magnets were always in the same temperature environment regardless of the undulator gap.[2,3] Cooling the beam pipes to ambient temperature would simplify the operation of the undulator lines since changes to the undulator gap or changes to the beam current would be transparent as far as temperature effects were concerned. Cooling the beam pipes would use already installed Process Chilled Water (PCW). There would be a cost, however, to upgrade the PCW system and to implement the rest of the beam pipe cooling system. A natural question to ask is whether we can avoid these costs by measuring the magnet temperatures and adjusting the undulator gaps to correct for magnet temperature effects. This note addresses this question. Other factors, such as any effects on the experiments, and effects of additional wear on the undulator drive systems, are not addressed.

The magnet temperatures can not be easily measured in the undulator lines. However, the magnet keeper temperatures are easily measured. We will study whether we can

[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, "Tests Of A Proposed Undulator Beam Pipe Cooling Method", LCLS-TN-22-4, February, 2022.

[3]Z. Wolf, "Tests Of A Proposed Beam Pipe Cooling Method On An LCLS Soft X-Ray Undulator", LCLS-TN-23-7, September, 2023.

determine the magnet temperatures to sufficient accuracy by measuring the magnet keeper temperatures. We suspect such a plan will work because the undulator hall has a 2 deg C temperature rise along its length so every undulator gap is already being set using temperature corrections from Resistance Temperature Detectors (RTDs) on the magnet keepers. But this is steady state and without a significant local heat source. We wish to determine whether dynamic measurements of the magnet keeper temperatures accurately give the magnet temperatures during changes of the undulator gaps and during changes of the beam power. We also wish to determine whether there are significant temperature gradients in the magnets due to the localized heating from the beam pipe which might cause the magnet keeper temperatures to be different than the magnet surface temperatures near the beam pipe. We will see that correcting the K values of both SXR and HXR undulators by approximating the magnet temperatures by the keeper temperatures and adjusting the undulator gap to correct for temperature effects is feasible.

2 Requirements

The LCLS-II undulator requirements come from a Physics Requirements Document.[4] The LCLS-II-HE undulator requirements come from a different Physics Requirements Document.[5] The requirements and related information to the tests in this note are briefly summarized below.

1. The minimum undulator gap for both the SXR and HXR lines is 7.2 mm. The maximum operational gap is larger than 20 mm. The beam pipe temperature will have the maximum effect on the undulator magnets at 7.2 mm gap. At gaps larger than 20 mm, beam pipe heating effects will be negligible as we will see below.

2. The accuracy for setting the undulator K value is $\Delta K/K = 3.0 \times 10^{-4}$ for the SXR line, 5.5×10^{-4} for the HE-SXR line, and 2.3×10^{-4} for the HXR line. These total errors include calibration errors, alignment errors, gap errors, etc. We wish to keep the error on K due to beam pipe temperature effects below approximately $\Delta K/K = 1 \times 10^{-4}$ in order to use only a fraction of the total error budget. Since the magnets have a temperature coefficient of $1/B \; dB/dT = 10^{-3}$ 1/deg C, and $1/B \; dB/dT = 1/K \; dK/dT$, we must know the magnet temperatures to 0.1 deg C to meet the imposed $\Delta K/K = 1 \times 10^{-4}$ tolerance.

3 Experimental Setup

3.1 SXR Undulator

The SXR undulator tests were performed in the undulator hall on maintenance days since an SXR undulator with a beam pipe installed was not available in the Magnetic Measurement Facility (MMF) due to ongoing HE-SXR undulator production measurements. Small

[4] H.-D. Nuhn et al., "Undulator System", LCLS-II Physics Requirements Document LCLSII-3.2-PR-0038-R3, June, 2017.

[5] 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.

thermistors were placed on the beam pipe and on the magnets in order to measure temperatures in the undulator gap. The thermistors are described in a technical note detailing the water cooling tests.[6] Figure 1 shows the thermistors. The small thermistors at the ends of the very fine wires give the primary temperature measurements for this note. Slightly larger thermistors with different calibrations, which are at the ends of the colored wires, were used as a second measurement in order to verify the measurements of the primary thermistors. The labeled thermistors in the photo were used to measure the beam pipe temperature. Below those thermistors are other thermistors used to measure the magnet temperatures. Not shown in the photo is a thermistor that was added to measure the air temperature. At the top of the photo is an RTD used by the control system and used for

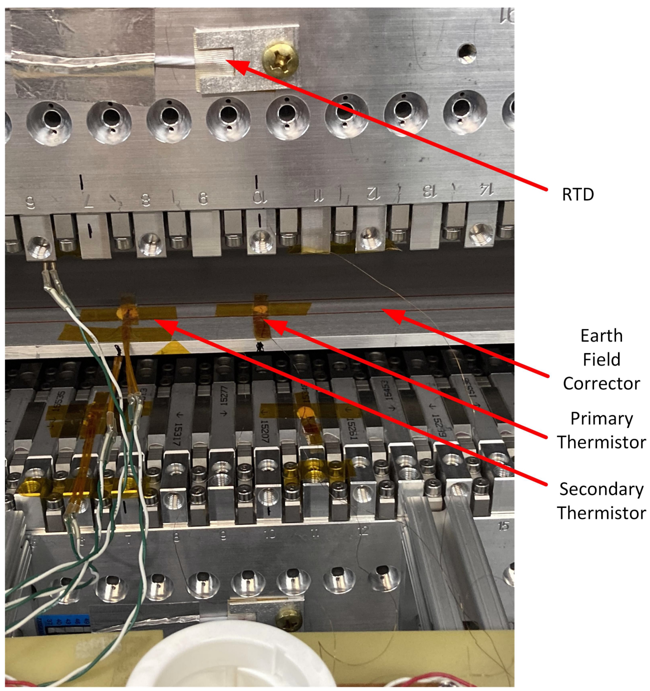

Figure 1: Small thermistors were placed in the SXR undulator gap to measure the temperature of the beam pipe and the undulator magnets.

this note to measure the magnet keeper temperature. The Earth field corrector windings, which are labeled in the photo, were used to heat the beam pipe. The power per unit length applied to the beam pipe was 3.3 W/m. The value 3.3 W/m is the maximum power used in the beam pipe design calculations.[7]

[6] Z. Wolf, "Tests Of A Proposed Beam Pipe Cooling Method On An LCLS Soft X-Ray Undulator", LCLS-TN-23-7, September, 2023.

[7] J. Carter, "Thermal and pressure drop analyses for the SXRU and HGVPU undulator vacuum chambers", APS_1692817, January, 2016.

3.2 HXR Undulator

The HXR undulator tests were performed in the MMF. This allowed ongoing tests instead of tests only on undulator hall maintenance days. The same thermistors were used as for the SXR undulator tests. The thermistor measurements are further detailed in a technical note on HXR beam pipe water cooling.[8] Figure 2 shows the thermistors used to measure the magnet temperatures. The thermistors used to measure the beam pipe temperatures are also visible, but harder to see. The earth field corrector windings are shown in the photo.

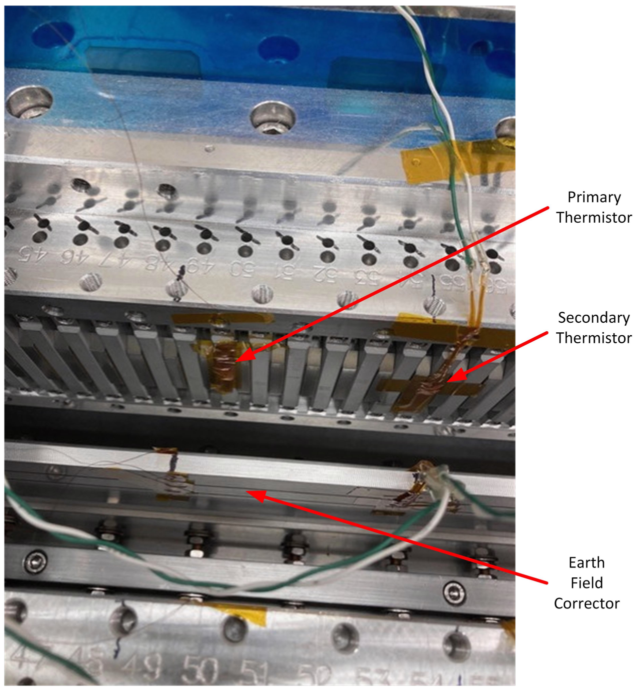

Figure 2: Small thermistors were placed in the HXR undulator gap to measure the temperature of the beam pipe and the undulator magnets.

RTDs from the control system were not installed on this undulator, so separate thermistors were installed to measure the magnet keeper, magnet strongback, girder, and air temperatures. These additional thermistors are shown under electrical tape in figure 3. Also shown is a photo from the undulator hall which gives the location of the control system's RTDs used to measure the keeper temperatures. In the MMF local power supplies were used to deliver power to the Earth field corrector windings. The applied power per unit length was 3.3 W/m.

[8] Z. Wolf, "Tests Of A Proposed Undulator Beam Pipe Cooling Method", LCLS-TN-22-4, February, 2022.

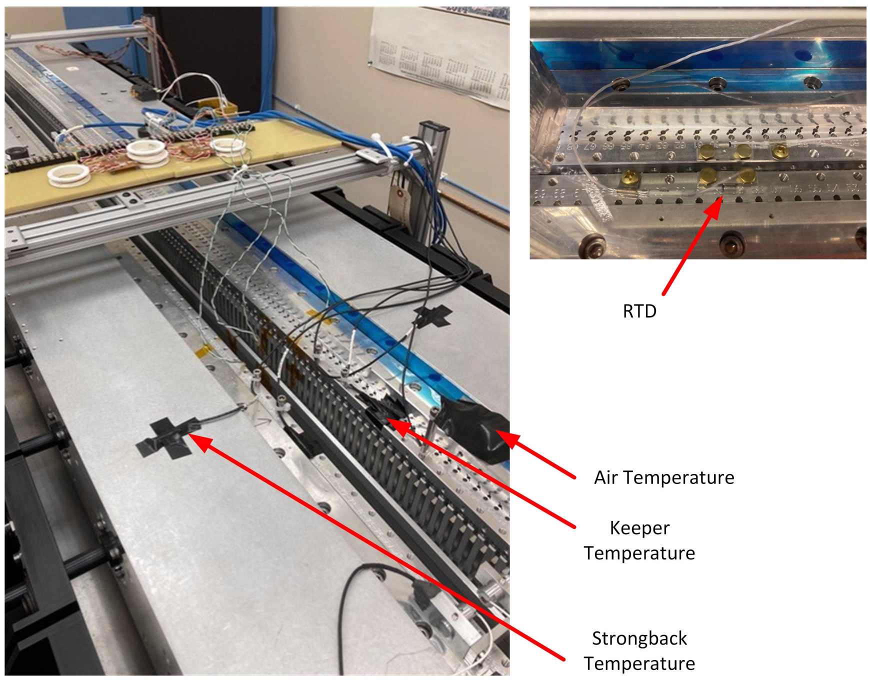

Figure 3: Thermistors were added to measure the magnet keeper, strongback, girder, and air temperatures. In the undulator hall, RTDs are used to measure the magnet keeper temperatures.

4 Test Results

4.1 SXR Undulator

Because tests on an SXR undulator were only performed in the undulator hall on maintenance days, limited data is available. To make sure we understand the limited measurements, a heat transfer model was made which agrees with the temperature measurements. The model gives insights into how the magnets and keepers are heated. We will see that the measured keeper temperatures are close to the magnet temperatures, as the model predicts, allowing for making approximations to the magnet temperatures. The model is for steady state heat transfer and does not include heat capacities needed for time varying effects. It turns out, however, that the keeper temperature measurements are close to the magnet temperature measurements even during transients when power is initially applied to the beam pipe, when power is turned off, and when the undulator gap is opened. A study of closing the undulator gap onto a warm beam pipe was only made for the HXR undulator as presented below, but we expect similar results for the SXR undulator. This section presents the SXR measurements and the heat transfer model results.

Figure 4 shows an interesting behavior of the beam pipe and magnet temperature changes relative to ambient temperature as power is applied to the beam pipe and as the undulator gap is opened. Changes in temperature are used in the plot in order to remove offset errors in the thermistor measurements. At the left of the plot, before time 18:00, the

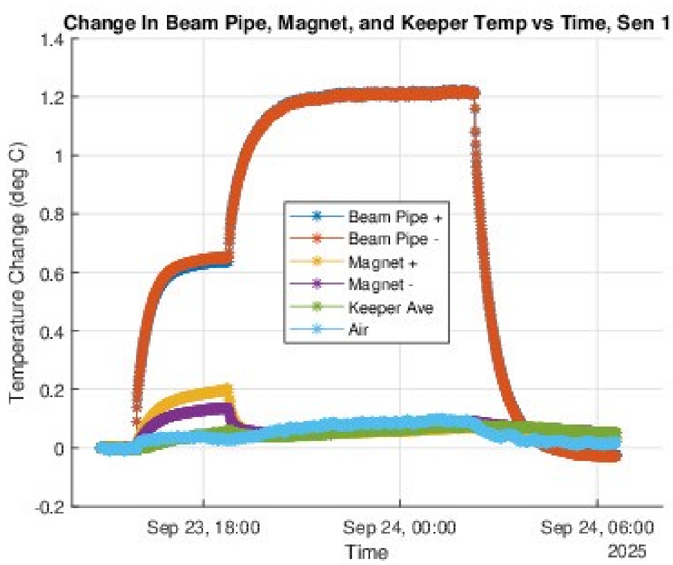

Figure 4: Beam pipe and magnet temperature changes from ambient temperature at 7.2 mm and 20 mm undulator gaps with 3.3 W/m applied to the beam pipe.

power into the beam pipe went from 0 to 3.3 W/m when the undulator gap was 7.2 mm. The change in temperatures is visible. The beam pipe temperature rose by approximately 0.65 deg C, and the magnet temperatures rose by approximately 0.2 deg C. The upper and lower magnets are at slightly different temperatures since the beam pipe wasn't perfectly centered. A little after hour 18:00, the undulator gap was opened to 20 mm by another user for a different test. The beam pipe temperature rose to approximately 1.2 deg C above ambient and the magnet temperature went to the ambient air temperature. This plot shows that at small undulator gap, the air between the beam pipe and the magnets acts like a thermal conductor. Heat leaves the beam pipe limiting how hot the beam pipe gets. Heat enters the magnets increasing their temperature. At large undulator gaps, however, the air between the beam pipe and the magnets insulates the beam pipe. The beam pipe temperature increases. Little heat flows to the magnets so they are near the ambient air temperature. We see that air is a fairly good heat conductor when it is in a thin layer at small undulator gap, and it is a good insulator at large undulator gap.

The difference between the magnet temperature and the keeper temperature is shown in figure 5 in yellow. The temperature difference rises gradually and goes to a constant value of

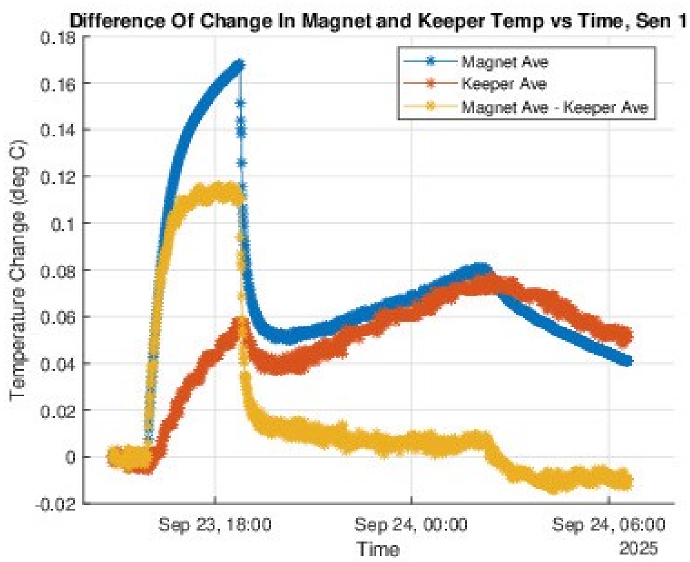

Figure 5: The difference between the magnet and keeper temperatures (yellow curve) goes to a constant value of 0.11 deg C at an undulator gap of 7.2 mm, and is approximately 0.01 deg C at a gap of 20 mm.

approximately 0.11 deg C at 7.2 mm gap. Then at 20 mm gap, the temperature difference falls gradually to approximately 0.01 deg C. The 0.11 deg C temperature difference at small gap is slightly larger than the tolerance value of 0.1 deg C, but is close. If the keeper temperature is used to correct K, the error on K will be at the 1.1×10^{-4} level and the performance of the SXR undulator line should not be significantly impacted. If the magnets had high thermal resistance, one might expect a large temperature drop across the magnets making the keeper temperature significantly different than the magnet face temperature being measured, but this is not the case. The keeper temperature gives an acceptable representation of the magnet temperature. Since the keeper temperature and magnet temperature are measured on different sides of the magnets, temperature differences in the magnets are below 0.11 deg C. So the fact that the magnets are being heated locally by the beam pipe should not have a large effect on the overall strength of the magnets since temperature differences in the magnets are small.

A model was used to study the thermal behavior of the beam pipe and magnets. The model is illustrated in figure 6. Power is put into the beam pipe which heats it, and the heat flux flows out of the beam pipe in three parallel paths. Each path is modeled as a one dimensional heat transfer problem. Heat flows into the upper undulator jaw through an air gap, then into the magnets, then into the magnet keepers, then into the strongback, and finally leaves the strongback through the metal-air interface. An identical heat path is provided by the lower jaw. The third path is into the beam pipe's support structure and then into the air. The beam pipe does not make physical contact with the undulator.

For each material, the heat flux J is given by the thermal conductivity times the gradient of the temperature. This leads to an approximate linear relationship between the heat flux and the temperature drop across each material.

$$J = k\frac{\Delta T}{L} \tag{1}$$

where k is the thermal conductivity, L is the length of the material, and ΔT is the temperature drop across the material. The heat transfer to air is given by

$$J = h\Delta T \tag{2}$$

where h is a heat transfer coefficient.

These equations are analogous to Ohm's law for a resistor. ΔT is analogous to the voltage drop across a resistor, $\frac{k}{L}$ and h are analogous to the inverse of resistance, and J is analogous to the current. The electric circuit analog is shown on the right side of figure 6. In the circuit from top to bottom, the undulator jaw resistors correspond to the thermal resistance of the air gap, magnets, keepers, strongback, and the metal-air interface. The beam pipe resistors correspond to the thermal resistance of the beam pipe and the thermal resistance of the beam pipe to air interface. The 3.3 W/m going into the beam pipe is equivalent to the current source.

The thermal resistances (L/k) for the different materials can be calculated from the thermal conductivities and the dimensions. The thermal resistance of the air gap depends on the undulator gap since the length of the air gap is half the difference between the undulator gap and the beam pipe height. From the equivalent circuit of a current source putting current into a resistor network, it is clear that when the thermal resistance of the air gap is small, the temperature (voltage equivalent) of the beam pipe will be lower than when the thermal resistance of the air gap is large. Also, more heat flows into the magnets when the thermal resistance of the air gap is small.

The equivalent circuit can be analyzed further. In figure 7 the fixed resistors have been combined and the parallel paths through the undulator jaws have also been combined. In the figure $R_g = R_a/2$, $R_j = (R_m + R_k + R_s + R_i)/2$, and $R_b = R_{bp} + R_{bpi}$, where the quantities on the right of the equal signs refer to figure 6. The total resistance of the parallel paths is

$$R_t = \frac{(R_g + R_j)R_b}{R_g + R_j + R_b} \tag{3}$$

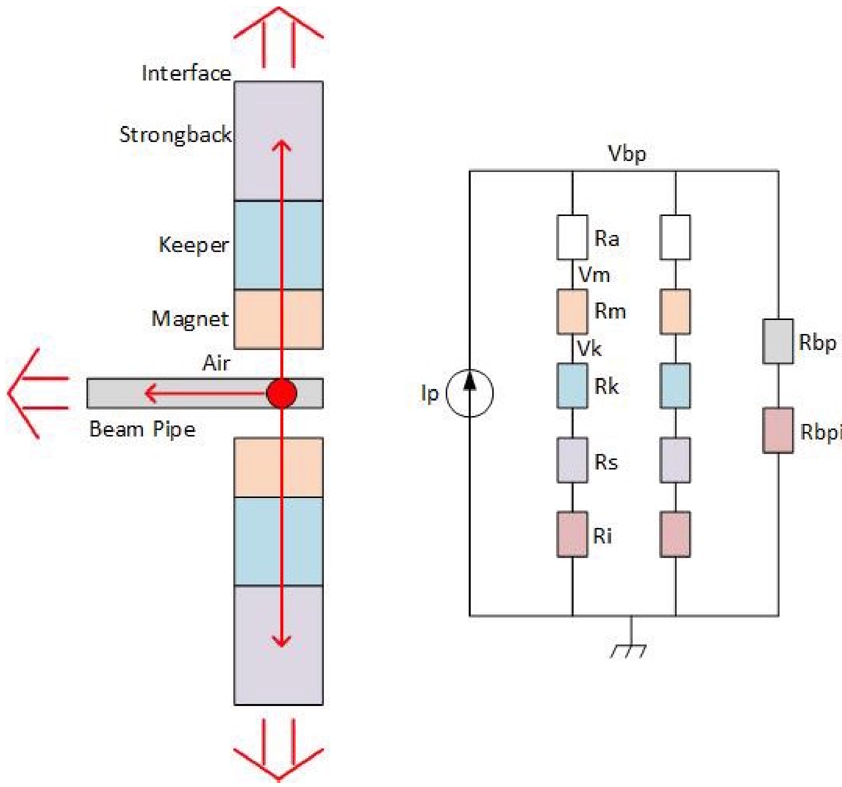

Figure 6: Model to explain the behavior of the beam pipe and magnet heating. In the equivalent circuit, the resistors from top to bottom are for the air gap, magnet, keeper, strongback, and strongback to air interface. Also from top to bottom are the beam pipe resistance and the beam pipe to air interface resistance.

The beam pipe voltage is given by $V_{bp} = I_p\, R_t$.

$$V_{bp} = I_p \frac{(R_g + R_j)R_b}{R_g + R_j + R_b} \tag{4}$$

The current through R_g is given by $I_g = V_{bp}/(R_g + R_j)$. Simplifying, this gives

$$\begin{aligned} I_g &= I_p\, R_t \frac{1}{R_g + R_j} \\ &= I_p \frac{R_b}{R_g + R_j + R_b} \end{aligned} \tag{5}$$

The voltage at the magnets is given by $V_m = I_g\, R_j$, or

$$V_m = I_p \frac{R_b R_j}{R_g + R_j + R_b} \tag{6}$$

The voltage at the keepers is given by $V_k = I_g(R_j - R_m)$, or

$$V_k = I_p \frac{R_b(R_j - R_m)}{R_g + R_j + R_b} \tag{7}$$

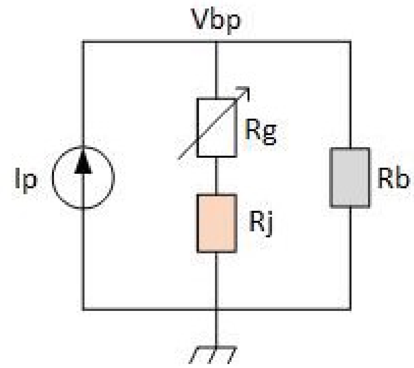

Figure 7: Simplified equivalent circuit for analysis.

The difference between the magnet and keeper voltages is given by

$$V_m - V_k = I_p \frac{R_b R_m}{R_g + R_j + R_b} \tag{8}$$

The SXR undulator 1-D heat transfer model was implemented in a computer program. Values of the thermal conductivities and heat transfer coefficients were obtained for the various materials. Dimensions for the various components were obtained from drawings. Some estimates were made of equivalent 1-D dimensions given the actual 3-D components. The thermal resistance of the magnets was calculated to include the effects of the steel poles. The thermal resistance of the air gap included a gap dependence of the air thermal conductivity as described in references. The other thermal resistances were calculated as L/k. The mathematics for the thermal model is the same as for the circuit model. The gap dependence of the air thermal conductivity added a small non-linearity to the model. Temperatures in the model are relative to ambient temperature, so the ambient temperature $T_{amb} = 0$. The model produced results agreeing with the data as shown below. The model is for heat transfer only and does not include heat capacities, so transient behavior is not included in the model.

Figure 8 shows the modeled thermal resistance of the undulator jaws and beam pipe as a function of gap. The thermal resistance of the beam pipe heat path is very low. The thermal resistance of the undulator jaw heat path is small at small gap and grows almost linearly with gap.

Figure 9 shows the heat flux going into one jaw and into the beam pipe as a function of undulator gap. The beam pipe cross section is smaller than the magnet cross section, so in addition to heat flux, we can also look at the power per unit length going into the magnets of both jaws combined and into the beam pipe. This is shown in figure 10. At small gap, the beam pipe and magnets have about the same power per unit length going into them. At large gap, almost all the heat is taken away by the beam pipe with only a small amount going into the magnets. The sum of the power per unit length going into both undulator jaws and into the beam pipe is equal to the applied power per unit length.

Figure 11 shows the temperature rise above ambient of the beam pipe, the magnets, and the magnet keepers as a function of undulator gap when 3.3 W/m is applied to the beam

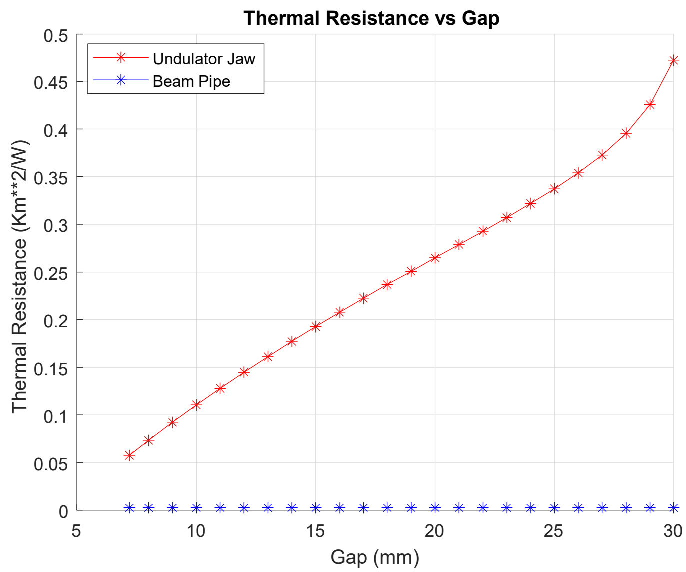

Figure 8: Total thermal resistance (sum of the individual thermal resistances) in units of Km^2/W of a single undulator jaw and of the beam pipe heat path.

pipe. Also shown in the figure are the measured temperature rises relative to ambient. The measurements agree fairly well with the model.

Figure 12 shows the temperature difference between the magnets and the keepers as a function of gap. The temperature difference between the magnets and the magnet keepers is small and only goes slightly above the tolerance limit of 0.1 deg C at small gap. If desired, one could use this plot to correct the steady state measured keeper temperature to the magnet temperature by adding the difference shown in the plot to the keeper temperature. This would reduce the error on K even further, although without this extra correction, K will be at or within the tolerance limit.

We conclude that in steady state, the keeper temperature gives the magnet temperature to within 0.11 deg C. Temperature differences within the magnets are below 0.11 deg C. When 3.3 W/m is applied to the beam pipe at 7.2 mm gap, the magnet temperature rise of 0.2 deg C is large enough that we need to correct the undulator K value for the magnet temperature. The correction for magnet temperature is done by adjusting the undulator gap. We can correct for magnet temperature using the measured keeper temperature and the difference is small enough that it will keep $\Delta K/K < 1.1 \times 10^{-4}$. The measured transient effects are in agreement with these conclusions. As power is applied to the beam pipe and as the undulator gap is opened, the thermal resistance of the magnets is low enough that the keeper temperature stays within 0.11 deg C of the magnet temperature as a function of time. A study of closing the undulator gap onto a warm beam pipe was not made for the SXR undulator, however, the study was made on an HXR undulator. We expect the measured transient effects to be applicable to SXR undulators. The HXR undulator results are detailed below.

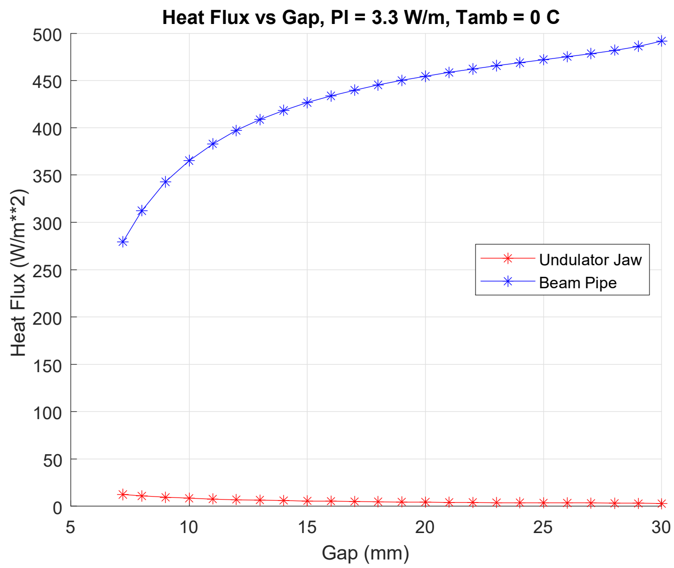

Figure 9: Heat flux J in units of W/m^2 going into one jaw and into the beam pipe. $T_{amb} = 0$ in the title refers to the temperatures in the model being relative to ambient temperature.

The estimated error $\Delta K/K < 1.1 \times 10^{-4}$ is expected to be conservative for the following reason. The magnets are magnetized longitudinally and the magnetic flux from the large face of the magnet goes into an undulator pole. The magnetic field in the undulator gap depends on the total flux going into each pole. With a constant temperature gradient along the transverse direction of the magnet, the flux going into each pole would correspond to the average magnet temperature rather than to the warmest temperature near the beam pipe, which is what we measure. The temperature difference between the magnet and the keeper that we measure is larger than the temperature difference between the average magnet temperature and the keeper. We provide an overestimate of the error on K by comparing the keeper temperature to the warmest magnet temperature. Since we can't measure the average magnet temperature, we will continue with our error estimate using measured quantities, however, we realize that the error on K is likely smaller than our estimate.

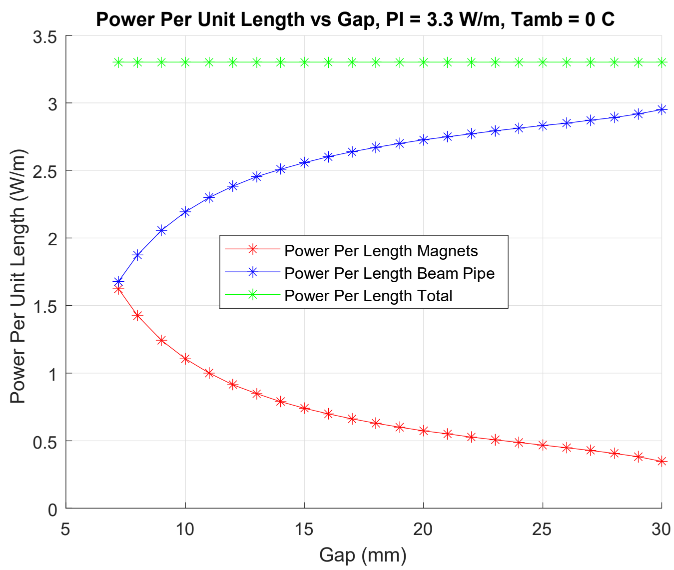

Figure 10: Power per unit length going into the magnets of both jaws and into the beam pipe. The sum gives the input power per unit length.

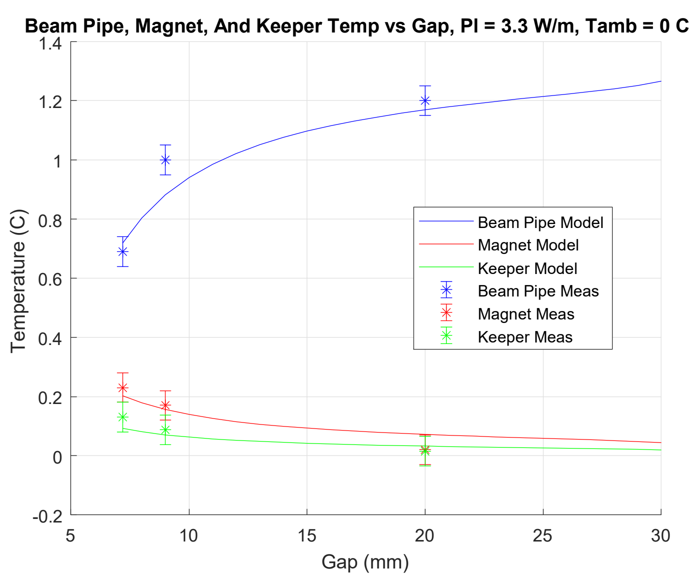

Figure 11: Temperature rise of the beam pipe, magnets, and magnet keepers as a function of undulator gap when 3.3 W/m is applied to the beam pipe.

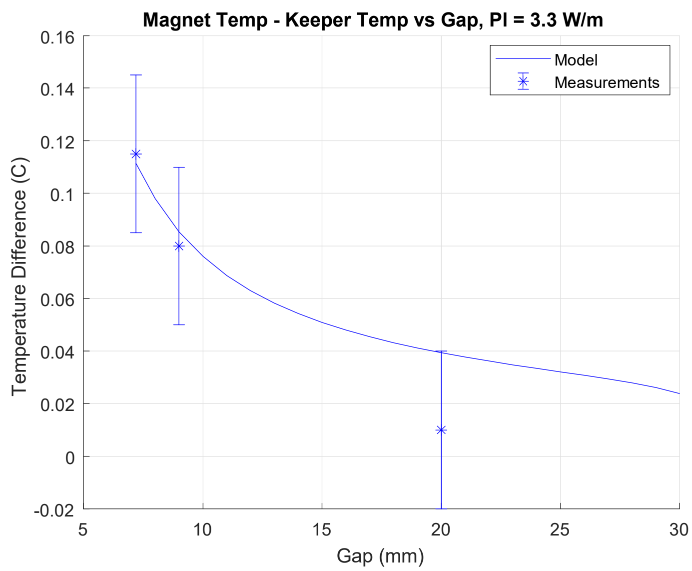

Figure 12: Temperature difference between the magnets and keepers as a function of gap.

4.2 HXR Undulator

A study of the effects of not cooling the beam pipe of an HXR undulator was performed in the MMF. Doing the measurements in the MMF allowed a more extensive set of measurements. Modeling the thermal behavior of the HXR undulator was not done. The thermal behavior is more complicated than for an SXR undulator because the beam pipe is thermally connected to the undulator girder, which is thermally connected back to the undulator jaws. This is illustrated in figure 13. Rather than trying to make a detailed

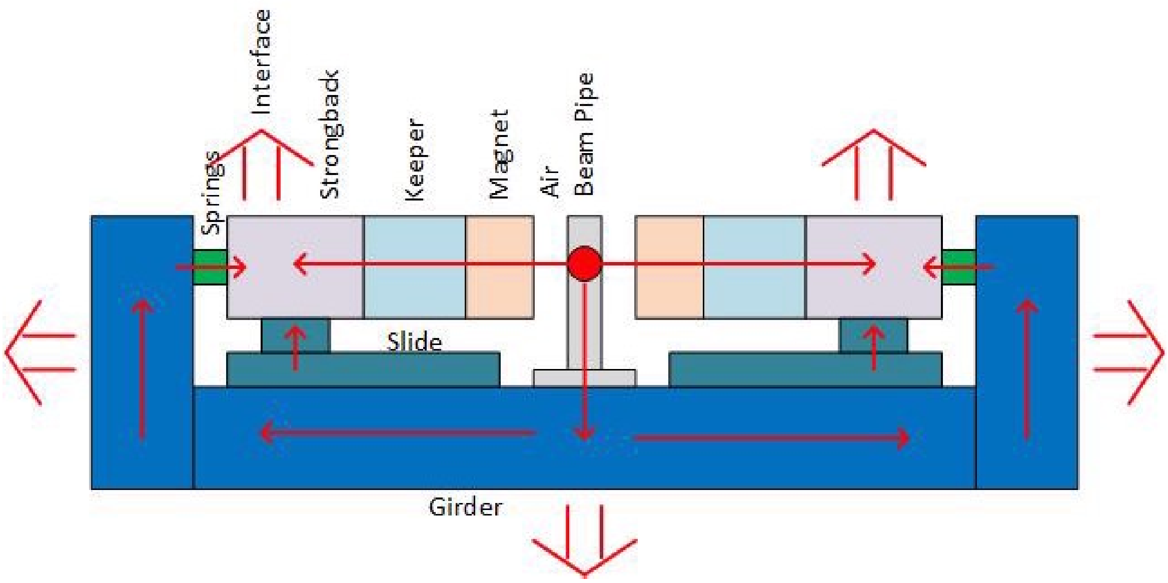

Figure 13: The beam pipe of the HXR undulators is thermally connected to the undulator jaws both through the air gap and through the girder making a thermal model complicated.

thermal model, we fit the measurements and use the form of fitting functions and the quality of the fits to test our understanding of the temperature rises. Intuitively, we expect the girder to be a good heat sink and to be near the air temperature. The form of the fitting functions of temperature rise vs gap should therefore be similar to the form coming from the SXR undulator model. We will demonstrate the validity of this form of the fitting functions below. We will also demonstrate that correcting the magnet temperature with the keeper temperature is a solution for keeping K within tolerance.

Magnet heating is largest at the smallest undulator gap of 7.2 mm. Figure 14 shows the beam pipe, magnet, and keeper temperature rises above ambient temperature at 7.2 mm gap when 3.3 W/m was put into the beam pipe from midday Nov 26 to Nov 29. As noted in the SXR undulator discussion, temperature changes are used in order to remove offset errors in the thermistor measurements. The temperature of the beam pipe rose by 0.8 deg C above ambient. The room air temperature is not as stable as in the undulator hall, however, so the error on the temperature rise is larger and is approximately 0.1 deg C. The magnet temperature rose by approximately 0.4 deg C above the air temperature, and the keeper temperature rose about 0.1 deg C less than that. The magnet and keeper

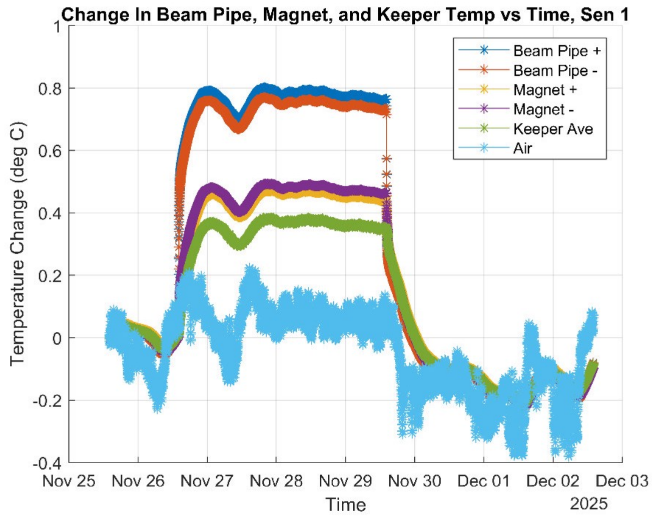

Figure 14: HXR temperature changes when 3.3 W/m was applied to the beam pipe from Nov 26 to Nov 29 while the gap was fixed at 7.2 mm.

temperatures and the difference between them is shown in figure 15. When 3.3 W/m is applied to the beam pipe at 7.2 mm undulator gap, the keeper temperature stayed within 0.1 deg C of the magnet temperature.

Temperature rise measurements were done at other undulator gaps. Fits were made to the beam pipe, magnet, and keeper temperature rises above ambient as a function of gap when 3.3 W/m is applied to the beam pipe. To do the fits, we assume the primary heat path to the magnets at small undulator gap is through the air gap. In this case the parallel resistor model of the SXR undulator should provide a good form for the fitting functions. We will try this form and see if the fits are still good at intermediate gaps. From the heat transfer model, we assume the gap dependence of the beam pipe temperature rise is given by

$$T_{bp} = P_l \frac{p_1\, g + p_2}{g + q_1} \tag{9}$$

where the p_i and q_i are gap independent parameters and g is the undulator gap. The p_i and q_i parameter notation is that of the Matlab fitting functions. From the heat transfer model, the form of the gap dependence of the temperature rise of the magnets is given by

$$T_m = P_l \frac{p_1}{g + q_1} \tag{10}$$

The parameter values are different than for the beam pipe even though the same Matlab notation is being used. Similarly, the form of the temperature rise of the keepers is given by

$$T_k = P_l \frac{p_1}{g + q_1} \tag{11}$$

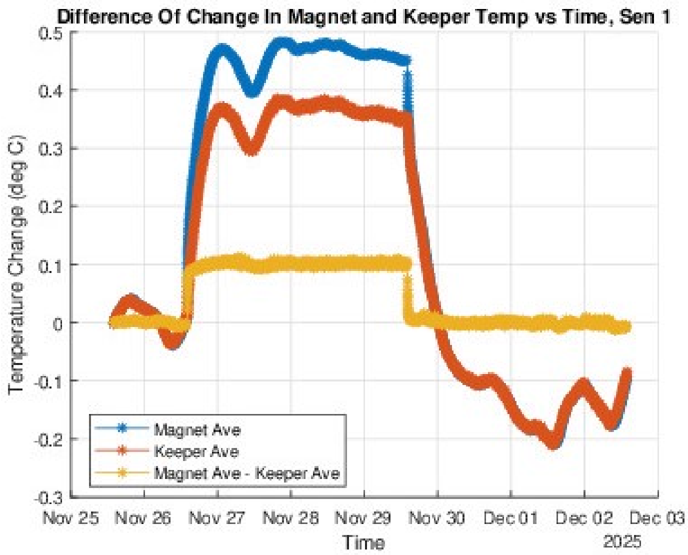

Figure 15: The difference between the magnet and keeper temperatures is approximately 0.1 deg C when 3.3 W/m is applied to the beam pipe when the gap is 7.2 mm.

Again, we only give the form of the fitting function in Matlab notation. The parameter values are different than for the magnets or the beam pipe.

A plot of the measured beam pipe, magnet, and keeper temperature rise at several undulator gaps is shown in figure 16. Measurements were done at undulator gaps of 7.2, 9.0, 10.0, 12.0, 16.0, and 20.0 mm. The plot shows the temperature rise above ambient when 3.3 W/m was applied to the beam pipe at the given fixed gaps. Error bars of 0.1 deg C are placed on each measured point. The error comes from the rather large room temperature variations during the measurements. Also shown in figure 16 are fits to the temperature rise measurements using the fitting functions given above. The fits agree well with the measurements in agreement with our understanding of the form of the fitting functions. The fit parameters are given in the figure.

The difference between the magnet and keeper temperatures is shown in figure 17. The error bars are much smaller because the temperature difference is insensitive to the room temperature variations. Also shown in the figure is the difference between the fits to the magnet and keeper temperature rises. The temperature rise difference is largest at small gap and decreases as the gap is increased. The maximum measured temperature difference is 0.1 deg C. Because the magnet and keeper temperatures are measured on different sides of the magnets, this also means that temperature differences within the magnets are only up to 0.1 deg C, which should not significantly affect undulator performance. We conclude that if the keeper temperature is used to correct for the magnet temperature, the errors on the undulator K value will be within tolerance. As noted for the SXR undulator, one could use this plot to correct the steady state measured keeper temperature to the magnet temperature by adding the difference shown in the plot to the keeper temperature. This

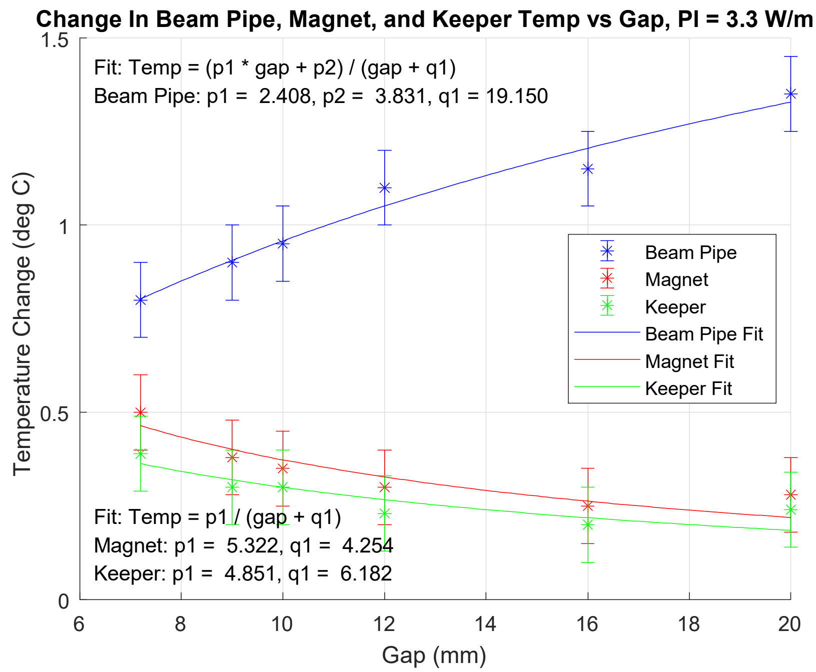

Figure 16: Temperature rise as a function of undulator gap when 3.3 W/m is applied to the beam pipe.

would reduce the error on K even further, although without this extra correction, K will be within the tolerance limit.

Up to now we have considered steady state temperature rise above ambient temperature. We now wish to consider transient effects. From figure 15, we see that when power is applied and removed from the beam pipe, the temperature changes are slow enough that the keeper temperature remains close to the magnet temperature. When 3.3 W/m is applied at 7.2 mm gap, the difference in temperature between the magnets and keepers rises smoothly from zero to the steady state value of 0.1 deg C with no overshoot. Similarly, when power is removed, the temperature difference goes smoothly from 0.1 deg C to zero with no overshoot. There are no transient effects to consider when power is applied or removed from the beam pipe.

Now consider what happens when the undulator gap is opened or closed onto a warm beam pipe. Suppose that the undulator gap is closed when 3.3 W/m is being deposited in the beam pipe. In figure 18, 3.3 W/m is constantly being applied to the beam pipe. Initially the gap is open at 20 mm. A little after Dec 12, the gap is closed to 7.2 mm. The beam pipe temperature drops by about 0.5 deg C. The magnet temperature increases by about 0.1 deg C, and the keeper temperature increases by about 0.05 deg C. Note that these values are less than the temperature changes in figure 14. This is because these are changes from the preheated conditions when power is applied at 20 mm gap. The changes are $T_m - T_{m0}$, and $T_k - T_{k0}$ for the magnets and keepers respectively, where T_{m0} and T_{k0} are the preheated temperatures at 20 mm gap. This is in contrast to figure 14 where the

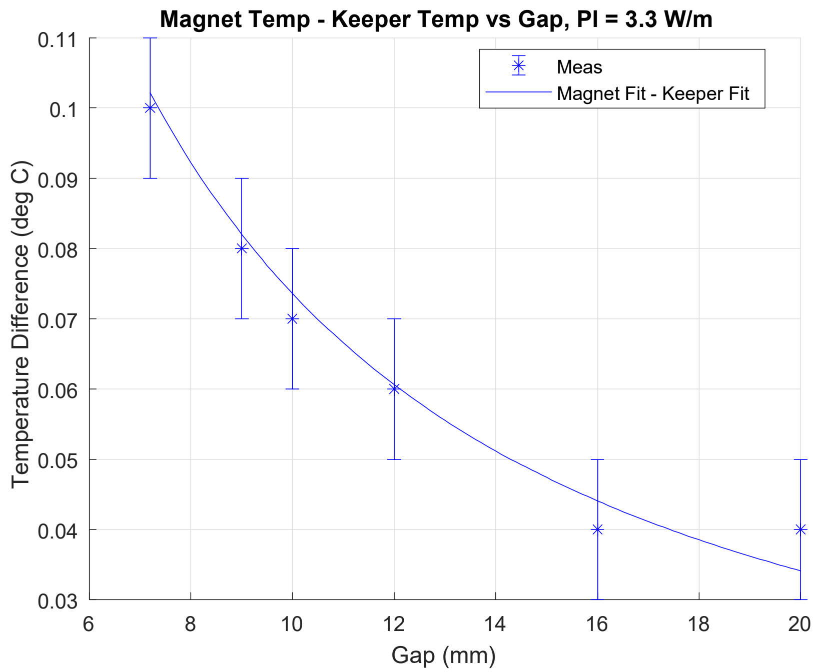

Figure 17: Steady state temperature difference between the magnets and the keepers.

changes are from initial ambient conditions, $T_m - T_0$, and $T_k - T_0$ for the magnets and keepers respectively, where T_0 is the ambient temperature. The air temperature changes add an uncertainty of about 0.1 deg C to the quoted temperature changes. After Dec 14, the gap is opened back to 20 mm. The beam pipe temperature rises by about 0.5 deg C, and the magnet and keeper temperatures drop by amounts similar to what they increased when the gap was closed.

The difference between the magnet temperature and the keeper temperature including the difference in the initial offsets is more clearly shown in figure 19. Since the initial temperatures T_{m0} and T_{k0} being subtracted are different, the temperature difference in figure 19 is $(T_m - T_{m0}) - (T_k - T_{k0})$. Up to now, $T_{m0} = T_{k0} = T_0$ and the temperature differences have been $(T_m - T_0) - (T_k - T_0) = T_m - T_k$, but this is presently not the case and initial temperatures must be considered. In figure 19 when the gap is closed, there is an overshoot in the change of magnet temperature relative to initial conditions compared to the change in keeper temperature relative to initial conditions. The magnets are rapidly brought near the warm beam pipe and heat up faster than the keepers which are further away from the beam pipe. There is a transient period where the magnet temperature is about 0.12 deg C warmer than the keeper temperature including the initial offset differences, while the steady state difference is 0.07 deg C. We take this 0.05 deg C difference between the peak and steady state values to be the amplitude of the transient. The transient period is expanded in figure 20. The transient period lasts for about 15 minutes. During this time, the corrections to the undulator K value using the keeper temperature will have larger errors. In steady state, the magnets change temperature 0.1 deg C more than the keepers,

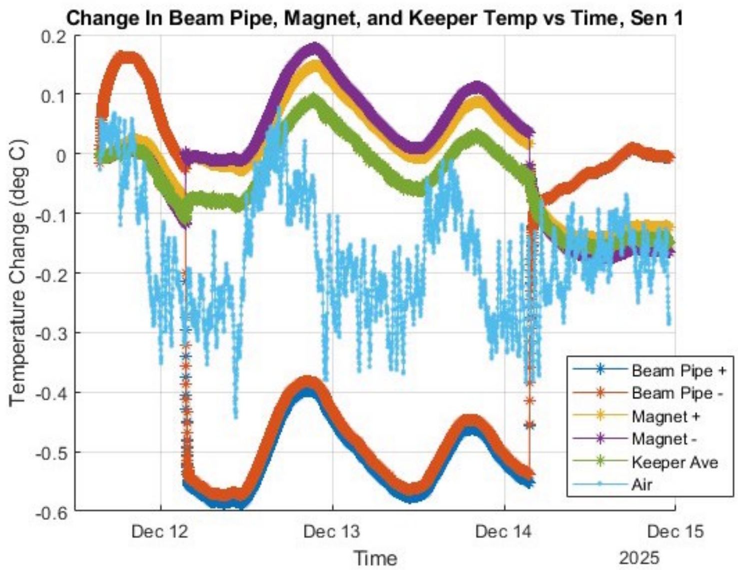

Figure 18: A constant 3.3 W/m is applied to the beam pipe as the undulator gap goes from 20 mm to 7.2 mm and then back to 20 mm.

and these changes are relative to the same ambient temperature. During the transient, the temperature difference without the initial value difference is the steady state value of 0.1 deg C plus the transient amplitude of 0.05 deg C, or 0.15 deg C. We expect the error on K during this time to be at the $\Delta K/K = 1.5 \times 10^{-4}$ level. Finally, we see from figure 19 that when the undulator gap is opened back to 20 mm on Dec 14, there is no overshoot. The keepers and magnets both cool at about the same rate.

To summarize, we found that when 3.3 W/m is applied to the beam pipe, the beam pipe heats the magnets when the undulator gap is small, and the magnet temperature increase will cause K to exceed the tolerance unless it is corrected. The correction is done by adjusting the undulator gap to account for the magnet temperature. Since the magnet temperature is hard to measure, we found that the keeper temperature can be used for the correction instead. In steady state, the keeper temperature gives the magnet temperature to within 0.1 deg C. Temperature differences within the magnets are below 0.1 deg C. Errors on the K value due to using the keeper temperature instead of the magnet temperature will be less than $\Delta K/K \leq 1 \times 10^{-4}$. As power is applied to or removed from the beam pipe, the thermal resistance of the magnets is low enough that the keeper temperature stays within 0.1 deg C of the magnet temperature as a function of time. When the undulator gap is opened away from the warm beam pipe, both the magnets and keepers cool at a similar rate keeping the temperature difference below 0.1 deg C. However, if the undulator gap is closed onto a warm beam pipe, the magnet temperature increases faster than the keeper temperature and there is a time period of about 15 minutes when there are extra errors coming from correcting K using the keeper temperature. The extra errors are expected to be at the $\Delta K/K \leq 1.5 \times 10^{-4}$ level during the transient period. These are expected to be conservative estimates as noted in the summary of the SXR undulator measurements.

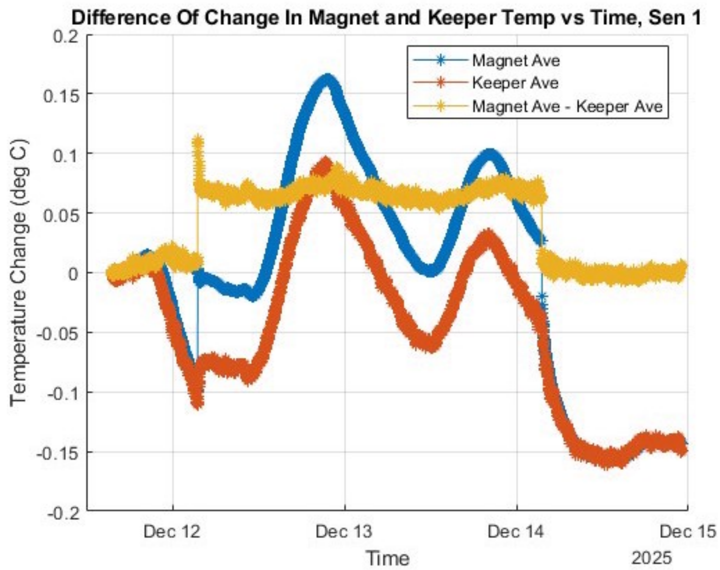

Figure 19: The difference between the magnet temperature and the keeper temperature as the gap is changed from 20 mm to 7.2 mm and back to 20 mm while 3.3 W/m is applied to the beam pipe.

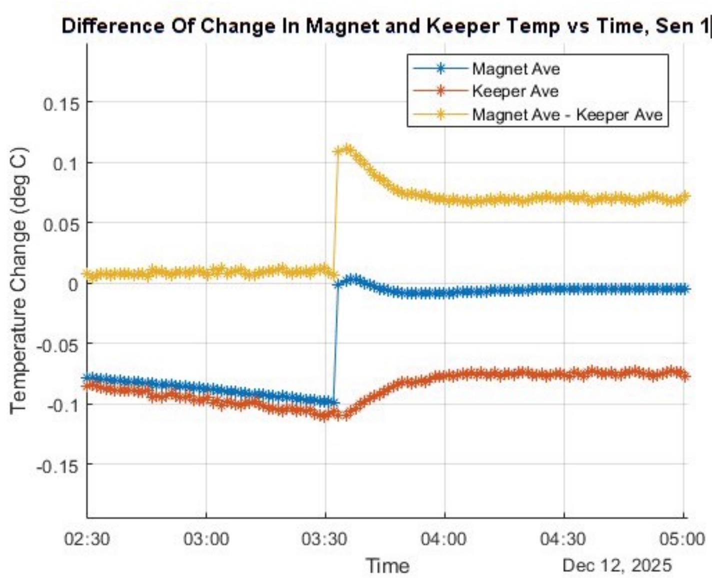

Figure 20: Expanded view of the transient period when the magnets are brought close to the warm beam pipe.

5 Conclusion

Energy from the high repetition electron beam will heat the beam pipes. At small undulator gaps, the magnet temperature will increase without water cooling. The undulator K value will change by more than the tolerance limit unless a correction is made. In this study we made measurements on both an SXR and HXR undulator and we made a heat transfer model to confirm our understanding of the measurements. From the measurements and the model, we determined that by measuring the magnet keeper temperature, the magnet temperature will be known to within about 0.1 deg C for both the SXR and HXR undulators. If a gap correction is made using the measured keeper temperature instead of the magnet temperature, the undulator K value will be off by up to 10^{-4} of its value, but will be within tolerance. The only exception will be when the undulator gap is suddenly closed onto a warm beam pipe. In this case there will be a transient period up to 15 minutes when the magnet to keeper temperature difference is larger than 0.1 deg C and the error on K using the keeper temperature for correction is expected to be about $\Delta K/K \leq 1.5 \times 10^{-4}$.

To do the temperature correction for K, the desired gap must be determined at regular intervals and the actual gap must be corrected when the actual K differs from the desired K by a fraction of the tolerance limit. If the desired gap and the actual K are calculated using the keeper temperature, errors $\Delta K/K \simeq 1 \times 10^{-4}$ will remain. This study showed that such a scheme should keep the undulator lines within their tolerance limits. However, no other effects, such as effects on the users when the gaps are changed during experiments, or effects on the lifetime of the undulator drive systems, were studied.

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