Effect Of SXR Beam Pipe Temperature On Undulator Magnet Temperature

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September 10, 2018

Abstract

This note documents a test that was made with an LCLS-II SXR undulator with a beam pipe installed in the Long Term Test Lab. The temperature of the beam pipe was changed and the undulator magnet temperature change was measured as a function of undulator gap. An analytical model was made of heat transfer from the beam pipe to the magnets which agrees with the measurements. Since the undulator K value depends on magnet temperature, the results should help set limits on how much the beam pipe temperature can deviate from the local ambient temperature.

1 Introduction[1]

The LCLS-II SXR undulators require[2] that the K value be set with an accuracy of $\Delta K/K = \pm 3 \times 10^{-4}$. The K value depends sensitively on temperature since the remnant field in the undulator magnets has a large temperature coefficient, typically $(1/B_r)(dB_r/dT) = 10^{-3}$ $1/°C$. The undulators will be calibrated at 20.0 $°C$ and at least one undulator will be measured over a range of temperatures so that the appropriate calibration can be determined at different ambient temperatures. Such measurements are required since the tunnel temperature varies by ± 1 $°C$. A complication is that the beam pipe of the SXR undulators is in close proximity to the undulator magnets and the beam pipe temperature influences the magnet temperature. If the beam pipe is not water cooled, or if the water for cooling the beam pipe is at a different temperature than the local ambient temperature, then a correction based only on the ambient temperature may be insufficient. It is difficult to measure the beam pipe and magnet temperature in the tunnel since small, delicate thermistors are required to measure in the small gap between the beam pipe and the magnets. Such measurements are best suited to a specialized laboratory environment and the measurement results applied to the tunnel environment. The laboratory measurements can be used to set limits on allowed beam pipe heating or the allowed cooling water temperature range. The laboratory measurements have been made and in this note we explore the relation between the beam pipe temperature and the undulator magnet temperature.

2 Setup

For this test we used the SXR undulator in the Long Term Test (LTT) area of the Magnetic Measurement Facility at SLAC. The undulator has a beam pipe mounted in it. Water cooling 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] H.-D. Nuhn, "Undulator System Physics Requirements Document", LCLSII-3.2-PR-0038-R3, June, 2017.

the beam pipe was installed for the test. Small thermistors were placed on the beam pipe and on the magnet blocks in the gap between the beam pipe and the undulator magnets. Temperature changes of the magnets were recorded as the beam pipe temperature was changed.

Figure 1 shows the beam pipe in the undulator gap at the minimum gap of 7.2 mm. At 7.2 mm

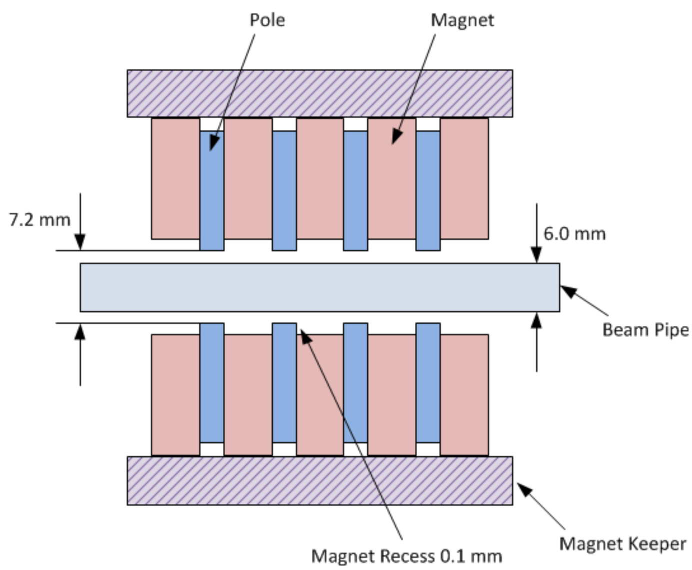

Figure 1: Undulator gap showing the magnet assemblies and beam pipe when the gap is 7.2 mm.

gap, the nominal distance between the beam pipe and the magnet poles is 0.6 mm, and the nominal distance between the beam pipe and the undulator magnets is 0.7 mm. The undulator gap was set using ceramic gauge blocks between the poles. An alignment crew centered the beam pipe in the undulator gap. We verified a clearance between the beam pipe and the undulator poles by using feeler gauges.

Figure 1 also shows that the magnet poles are smaller than the magnets and are not in good thermal contact with the magnet keeper which holds the assembly. In contrast, the magnets are held in contact with the keeper, which is a large aluminum structure at ambient temperature. We will return to this topic when we discuss a model of the heat flow from the beam pipe, through the magnets, to the magnet keeper at ambient temperature.

Small thermistors 0.280 mm in diameter[3] were placed in contact with the undulator magnets using thermal paste[4]. Two layers of 0.025 mm thick Kapton tape were used to secure the thermistors in place and to insulate them from the air above them. This is illustrated in figure 2. The same method was used to attach the thermistors to the beam pipe. Thermal paste made good thermal contact between the thermistor and the beam pipe, and two layers of Kapton tape insulated the thermistor from the surrounding air. A data acquisition unit[5] was used to measure the resistance of the thermistors and a calibration supplied by the manufacturer was applied to determine the temperature.

In order to set the beam pipe temperature, water was supplied using a commercial chiller[6]. Using water to control the beam pipe temperature provided temperature stability and rapid temperature changes which were needed for the measurements. The water temperature was measured using

[3]Simitec model 223Fμ3122-07U015 thermistors.
[4]Arctic type MX-4 thermal paste.
[5]Keysight model 34970A data acquisition unit with a 34901A multiplexer card.
[6]Thermo Scientific model Neslab Thermoflex 900-2500 chiller.

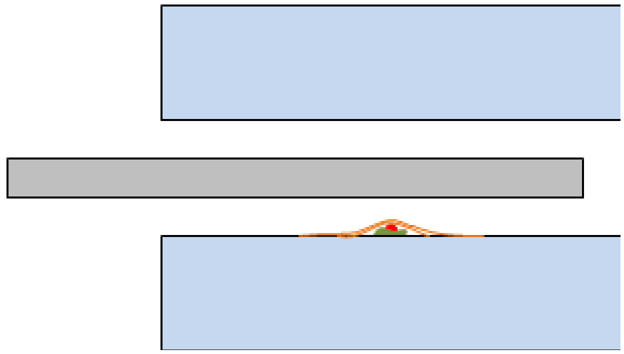

Figure 2: Thermistors (red) were placed in contact with the magnets using thermal paste (green) and insulated from the air above with Kapton tape (orange).

thermistors[7] with a manufacturer supplied calibration and the data acquisition unit mentioned above.

The LTT area does not have good temperature control which complicates the measurements. The air conditioner in the LTT area uses a cold refrigerant and an on-off control. Figure 3 shows a plot of the ambient temperature in the LTT area during a measurement. The rapid cycling of the

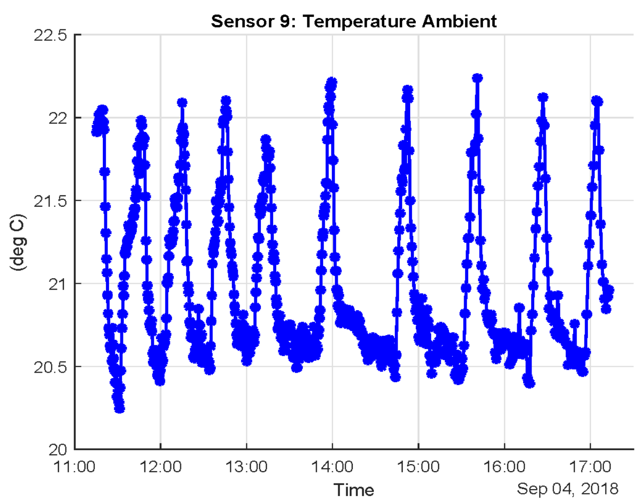

Figure 3: Ambient temperature in the LTT lab during a measurement with 25 mm undulator gap.

air conditioner gets averaged out by the thermal mass of the magnets and the beam pipe, however, drifts in the long term average temperature add noise to the measurements. Figure 4 shows the magnet temperature during the time that the fluctuating ambient temperature was measured. The undulator gap was 25 mm giving a maximal air flow to the magnets for the gaps considered in this note. There is a long, slow drift of 0.05 $^\circ C$ with fluctuations on the order of 0.02 $^\circ C$. These fluctuations largely set the size of the measurement errors. The long, slow drift was larger for other

[7] Semitec model 103JT-075 thermistors.

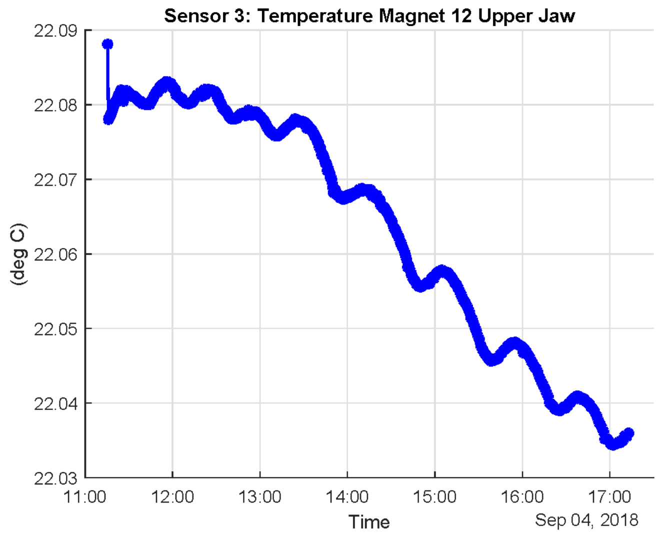

Figure 4: Magnet temperature during the previous ambient temperature measurements.

measurements (0.2 $^{\circ}C$ in figure 7 below), however, its linear component can be taken out with a baseline subtraction as discussed below.

In order to measure small temperature changes of the magnets in the LTT, the signals were modulated by varying the beam pipe temperature and looking at the magnet temperature variation. For all measurements, the water chiller temperature was first set to 20.0 $^{\circ}C$ and all temperatures were recorded for about one hour until equilibrium was established. The water temperature was then raised to 21.0 $^{\circ}C$ for two hours and all temperature were recorded. Finally, the water temperature was set back to 20.0 $^{\circ}C$ for one hour while all temperatures were recorded. A linear fit was made to the baseline 20.0 $^{\circ}C$ measurements. The baseline fit was subtracted from the measurements. The temperature rise during the two hour period of 21.0 $^{\circ}C$ water was then recorded.

Figure 5 is a representative plot of the beam pipe temperature during a test with 7.2 mm undulator gap. There is some overshoot in the chiller, but the temperature quickly settles. There is also an offset error either in the thermistors or in the chiller, but the offset will be subtracted using the baseline. A linear fit to the red points was used to determine the baseline. When the baseline is subtracted from the measurements, we get the temperature rise shown in figure 6. The water temperature rise is about 0.95 $^{\circ}C$.

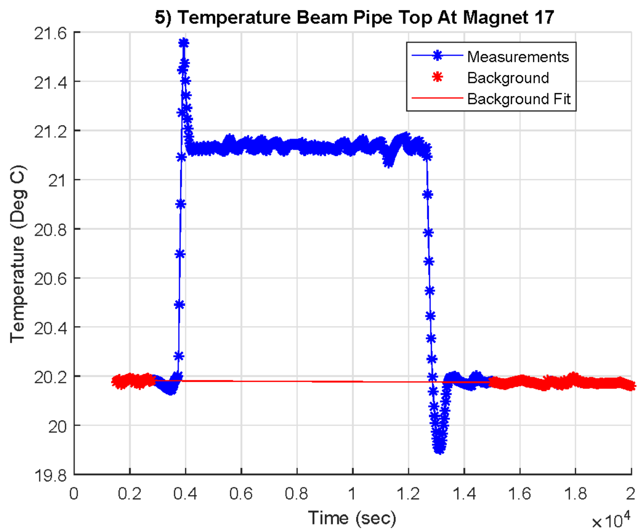

Figure 5: Beam pipe temperature during the test when the undulator gap was 7.2 mm. A linear fit was made to the red points and used for a baseline subtraction.

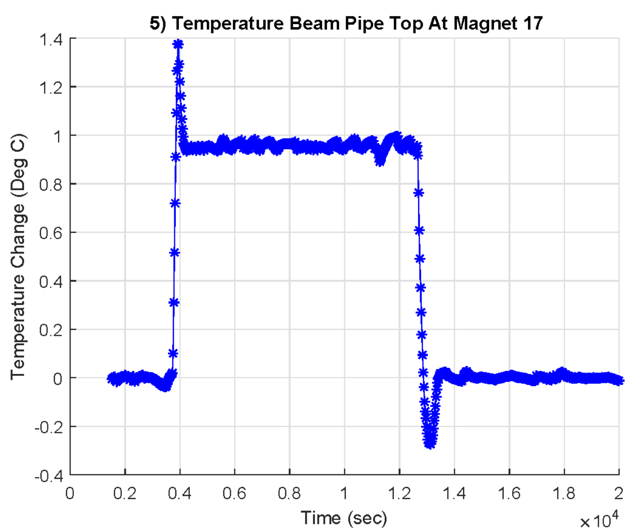

Figure 6: Beam pipe temperature after the baseline was subtracted. The plot shows the temperature rise.

Figure 7 is a representative plot of the magnet temperature during the test with 7.2 mm undulator gap. The red points again were used in a linear fit to determine the baseline. The temperature

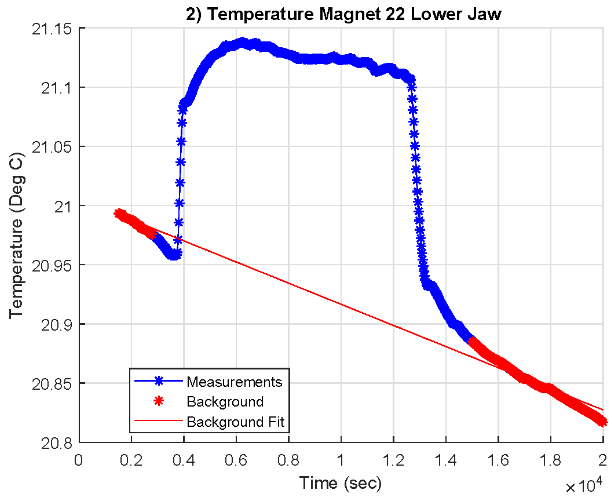

Figure 7: Representative magnet temperature measurement during the run where the undulator gap was 7.2 mm and the beam pipe water temperature rose 1 $^{\circ}C$.

rise with the baseline subtracted is shown in figure 8. The temperature rise of the magnet was approximately 0.2 $^{\circ}C$ when the beam pipe temperature was raised by about 1 $^{\circ}C$. The error on the magnet temperature rise appears to be roughly 0.02 $^{\circ}C$.

Four thermistors were placed on the magnets, two on the upper jaw 10 magnets apart, and two on the lower jaw 10 magnets apart. Two thermistors were placed on the beam pipe, one on top of the beam axis and one on the bottom under the beam axis. One thermistor was placed on the water inlet to the beam pipe and one thermistor was placed on the water outlet of the beam pipe. One thermistor measured the ambient air temperature. All thermistors measuring magnet temperatures gave similar measurements, and all thermistors measuring the beam pipe temperature gave similar measurements. The four magnet temperature rise measurements were averaged and the average magnet temperature rise as a function of undulator gap was plotted. This plot will be shown in a later section after a model is analyzed so that we can fit the measurements and interpret the results.

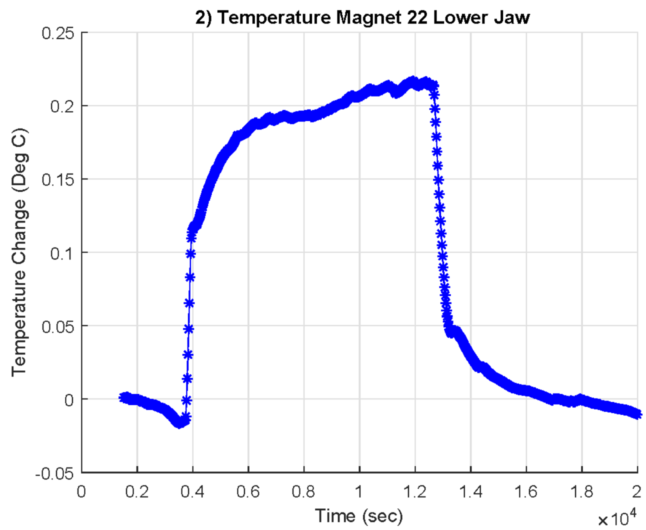

Figure 8: Magnet temperature rise after the baseline was subtracted.

3 Model

In order to fit the temperature rise of the magnets as a function of undulator gap, the functional form of the fit must be determined. We use a one dimensional model to determine the functional form of the fit. The model also gives insight into the results and valuable checks that the results seem correct.

Figure 9 illustrates the model. The beam pipe is at temperature T_b. Region 1 of length d_1 is

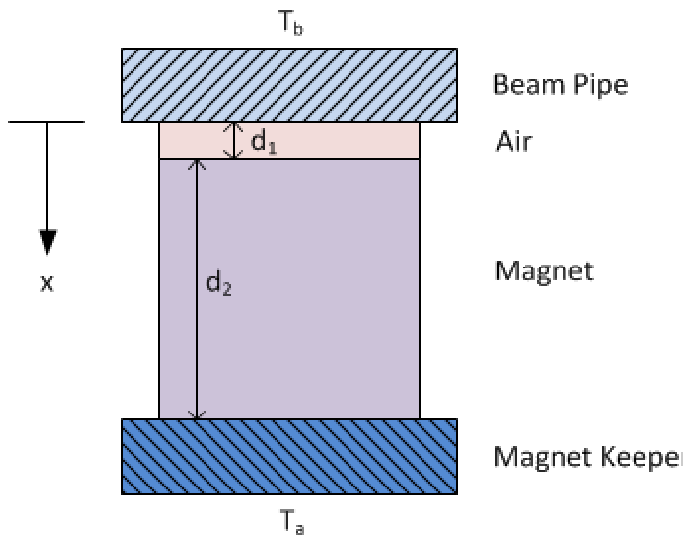

Figure 9: One dimensional model of heat flow from the beam pipe at temperature T_b to the magnet keeper at ambient temperature T_a.

the air gap between the beam pipe and the undulator magnets. Region 2 of length d_2 is the magnet assembly. The poles are smaller than the magnets and they don't have good thermal contact to the magnet keepers, so we assume they are at the magnet temperature and don't otherwise include them in the model. The magnet base is connected to the keeper at ambient temperature T_a. In regions 1 and 2 there is a heat flux from the temperature gradient

$$J = k\frac{\partial T}{\partial x} \tag{1}$$

where k is the thermal conductivity appropriate to each region. Gradients in the heat flux cause temperature changes in time

$$\frac{\partial J}{\partial x} = c\frac{\partial T}{\partial t} \tag{2}$$

where c is the heat capacity. In steady state

$$\frac{\partial T}{\partial t} = 0 \tag{3}$$

The steady state temperature profile is then determined by

$$\frac{\partial^2 T}{\partial x^2} = 0 \tag{4}$$

whose solution is

$$T(x) = ax + b \tag{5}$$

where $x = 0$ is at the beam pipe and x increases toward the magnet keeper. In region 1, the air gap, the temperature is

$$T_1(x) = a_1 x + b_1 \tag{6}$$

In region 2, the magnet assembly, the temperature is given by

$$T_2(x) = a_2 x + b_2 \tag{7}$$

The boundary conditions are

$$\begin{aligned} T_1(0) &= T_b & (8)\\ T_1(d_1) &= T_2(d_1) & (9)\\ J_1(d_1) &= J_2(d_1) & (10)\\ T_2(d_1+d_2) &= T_a & (11) \end{aligned}$$

In terms of the parameters in the equations for the temperature distribution, the boundary conditions become

$$\begin{aligned} b_1 &= T_b & (12)\\ a_1 d_1 + b_1 &= a_2 d_1 + b_2 & (13)\\ k_1 a_1 &= k_2 a_2 & (14)\\ a_2(d_1+d_2) + b_2 &= T_a & (15) \end{aligned}$$

When we solve these four equations for a_1, b_1, a_2, and b_2, we find that the temperature distribution is given by

$$\begin{aligned} T_1(x) &= k_2 \frac{T_a - T_b}{k_2 d_1 + k_1 d_2} x + T_b & (16)\\ T_2(x) &= k_1 \frac{T_a - T_b}{k_2 d_1 + k_1 d_2}(x - d_1) + k_2 \frac{T_a - T_b}{k_2 d_1 + k_1 d_2} d_1 + T_b & (17) \end{aligned}$$

At $x = d_1$, the surface magnet temperature where we measure is

$$T_m = (T_a - T_b)\,\frac{k_2 d_1}{k_2 d_1 + k_1 d_2} + T_b \tag{18}$$

When the beam pipe temperature changes and after equilibrium is reached, the change in the magnet temperature at the surface is

$$\begin{aligned} \delta T_m &= \left(1 - \frac{k_2 d_1}{k_2 d_1 + k_1 d_2}\right)\delta T_b & (19)\\ &= \frac{k_1 d_2}{k_2 d_1 + k_1 d_2}\delta T_b & (20) \end{aligned}$$

When the ambient temperature changes and after equilibrium is reached, the change in the magnet temperature at the surface is

$$\delta T_m = \frac{k_2 d_1}{k_2 d_1 + k_1 d_2}\delta T_a \tag{21}$$

We can estimate the size of the temperature changes by putting in the parameter values. The thermal conductivity of still air is[8]

$$k_1 = 0.024\ \frac{\mathrm{W}}{\mathrm{mK}} \tag{22}$$

[8] www.engineeringtoolbox.com

The thermal conductivity of NdFeB magnets is[9]

$$k_2 = 10\ \frac{\mathrm{W}}{\mathrm{mK}} \tag{23}$$

When the gap is 7.2 mm the distance between the beam pipe and the magnets is

$$d_1 = 0.7\ \mathrm{mm} \tag{24}$$

For distance d_2 we take the height of the magnet blocks since the bottom of the magnet blocks is in contact with the magnet keeper.

$$d_2 = 56.5\ \mathrm{mm} \tag{25}$$

Using these values, we find

$$\delta T_m = 0.16\ \delta T_b \tag{26}$$

and

$$\delta T_m = 0.84\ \delta T_a \tag{27}$$

We conclude from the model that the measured temperature change of the surface of the magnet should be on the order of 0.16 $^\circ C$ for a 1 $^\circ C$ temperature change of the beam pipe. We also conclude that the measurement is sensitive to ambient air temperature changes. A 1 $^\circ C$ ambient change produces a 0.84 $^\circ C$ change in the magnet surface temperature once equilibrium has been established. The thermal mass of the magnet assemblies will filter out the rapid temperature swings from the air conditioner, however, for the measurement to work, the modulation of the beam pipe temperature must take place on a time scale short enough that a linear fit can be used to take out the ambient temperature drift.

The measurements for this test can be used to predict the effect of the beam pipe temperature in the tunnel. From equation 18,

$$T_m = (T_a - T_b)\,\frac{k_2 d_1}{k_2 d_1 + k_1 d_2} + T_b \tag{28}$$

Suppose the beam pipe is kept at 20.0 $^\circ C$ and the ambient temperature is 21.0 $^\circ C$. We would find using the estimates above that the magnet temperature on its surface was

$$T_m = 20.84\ ^\circ C \tag{29}$$

If we only measured the 21.0 $^\circ C$ ambient undulator temperature away from the beam pipe, we would make an error when we corrected the K value because of the 0.16 $^\circ C$ magnet temperature deviation.

The one dimensional model lets us determine the functional form of the fit to the measurements of magnet temperature rise as a function of undulator gap for a 1.0 $^\circ C$ change in beam pipe temperature. From equation 19

$$\delta T_m = \frac{k_1 d_2}{k_2 d_1 + k_1 d_2}\delta T_b \tag{30}$$

The air gap between the beam pipe and the magnet is related to the undulator gap by

$$g = 2(d_1 - r) + w \tag{31}$$

where g is the undulator gap determined by the pole separation, w is the beam pipe thickness, and r is the recess distance of the magnets from the poles.. Inserting this expression in equation 19, we find

$$\delta T_m = \frac{k_1 d_2}{k_2\left[\frac{1}{2}(g-w) + r\right] + k_1 d_2}\delta T_b \tag{32}$$

[9] www.vacuumschmelze.com. A range of 5 to 15 W/mK was given and the midpoint was used.

or

$$\delta T_m = \frac{2\frac{k_1}{k_2}d_2}{g - w + 2r + 2\frac{k_1}{k_2}d_2}\delta T_b \tag{33}$$

The functional form of the fit is then

$$\delta T_m = \frac{p_1}{g + q_1}\delta T_b \tag{34}$$

where p_1 and q_1 are the fit parameters. Using the values given previously for the parameters, and using $w = 6$ mm and $r = 0.1$ mm, the expected fit parameters from the model are

$$p_1 = 0.271 \text{ mm} \tag{35}$$
$$q_1 = -5.53 \text{ mm} \tag{36}$$

4 Measurements

The four thermistors on the undulator magnets all gave a similar temperature rise when the water temperature was increased by 1.0 $°C$. The magnet temperature rises were averaged and the average magnet temperature rise at different undulator gaps is plotted in figure 10. At 7.2 mm gap, the measured average magnet temperature rise was 0.2 $°C$. An error bar of 0.02 $°C$, based on an estimate of how well the temperature rise could be determined, is placed on each point. A fit to

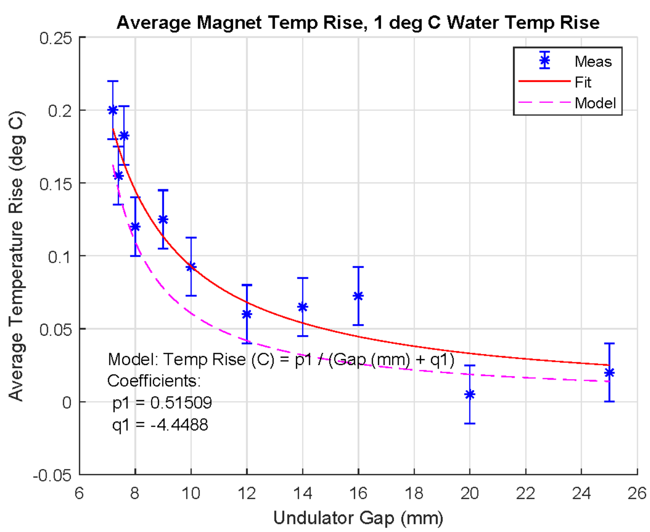

Figure 10: Magnet surface temperature rise as a function of undulator gap for a 1 $°C$ beam pipe temperature rise.

the magnet temperature rise as a function of gap was made using the functional form determined in the previous section. The fit parameters are given in the plot. Also in the plot is a curve of the prediction from the model derived in the previous section. The agreement of the model to the data is fairly good for a simple model with no free parameters. The residuals to the fit are plotted in figure 11. The rms of the residuals is 0.019 $°C$. This is in line with the expected error from using a linear fit to do ambient temperature drift corrections. The rms of the residuals from the model is 0.021 $°C$, slightly worse than the fit.

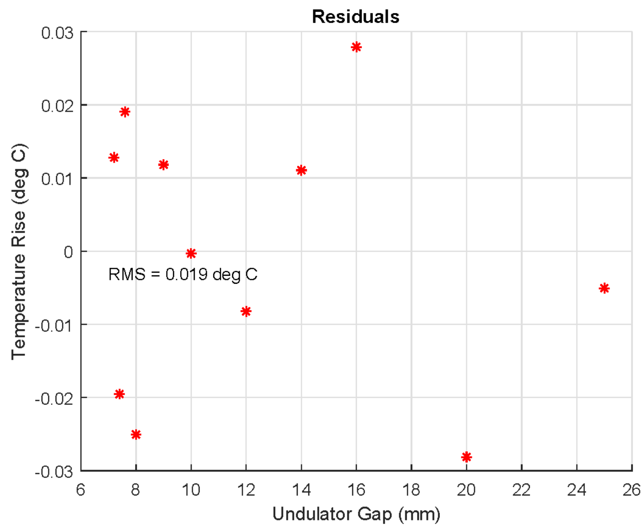

Figure 11: Residuals to the fit of magnet temperature rise as a function of undulator gap.

The fit gives a temperature rise of the magnets of 0.187 $^\circ C$ at 7.2 mm gap on the surface in the undulator gap. If the temperature varies linearly throughout the magnets to ambient temperature at their base, the average temperature rise will be approximately 0.1 $^\circ C$ at 7.2 mm gap. The magnet changes strength by

$$\frac{1}{B_r}\frac{dB_r}{dT} = 10^{-3}\ \frac{1}{^\circ C} \tag{37}$$

We expect the effect on the undulator K value to be

$$\frac{\Delta K}{K} = \frac{\Delta B_r}{B_r} = 1 \times 10^{-4} \tag{38}$$

for the average 0.1 $^\circ C$ magnet temperature difference when the beam pipe temperature is 1 $^\circ C$ different than ambient and the ambient temperature is used to correct K. This effect uses up about one third of the tolerance on setting K, a significant amount.

5 Conclusion

A beam pipe temperature change of 1 $^\circ C$ causes a surface temperature change of the magnets by 0.2 $^\circ C$ at 7.2 mm gap. If unaccounted for, this will use up a significant amount of the tolerance on K. It will also introduce temperature gradients in the magnets whose effect has not been measured. The measured temperature rise of the magnets is in rough agreement with a one-dimensional thermal model of the system.

Acknowledgements
I am grateful to Heinz-Dieter Nuhn and Yurii Levashov for discussions about this work.