Tests Of A Proposed Beam Pipe Cooling Method On An LCLS Soft X-Ray Undulator

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Abstract

Tests of a proposed method to cool the LCLS undulator beam pipes have been done previously on a hard x-ray undulator. Recently, the tests were repeated on a soft x-ray undulator. This note documents the results of those tests.

1 Introduction[1]

A previous note documented the need to cool the undulator beam pipes when the LCLS-II electron beam reaches a high repetition rate.[2] The note proposed a plan to cool the beam pipes by starting with chilled processed water and heating it to the local air temperature before running it through the beam pipes. In this way, each beam pipe is at the local air temperature, and when the undulator gap is opened or closed, the magnets are always in the same temperature environment. This eliminates temperature fluctuations and gradients so that existing magnet temperature measurements made on the magnet keepers will continue to accurately give the magnet temperature. The previously referenced note described tests on a hard x-ray undulator (HXU). The present work is a continuation of the beam pipe cooling effort, and this note presents results from repeating the HXU tests on a soft x-ray undulator (SXU).

2 Experimental Setup

The SXU tests were performed in the temperature conditioning area of the Magnetic Measurement Facility. The same water system and data logging system were used for the SXU tests as for the previous HXU tests. The water was run in parallel through the two chambers of the beam pipe, as it was for the HXU. The setup is shown in figures 1 and 2.

The SXU beam pipe is similar to the HXU beam pipe in cross section, but it is mounted differently. The SXU and HXU beam pipes in their undulators are shown in figure 3. The HXU beam pipe, shown in the right of the figure, is mounted vertically on the girder

[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.

Figure 1: Experimental setup showing the water temperature control system on the left, the water chiller in the middle, a rack with power supplies on the right, and the undulator in the background.

and the undulator jaws and spring cages enclose it. This limits the air cooling of the beam pipe tending to raise its temperature. It also thermally connects the beam pipe to the girder, undulator jaws, and magnets using heat conduction through the metals which tends to raise the magnet temperatures. In contrast, the SXU beam pipe, shown in the left of the figure, is mounted on pedestals at each end of the undulator. The tip of the beam pipe enters the gap from the side of the undulator. The entire surface of the beam pipe support is exposed to air for convective cooling. There is no metallic contact between the undulator and beam pipe for heat conduction. There is only the higher thermal resistance air gap for heat conduction from the beam pipe to the magnets. These effects tend to limit the beam pipe temperature and also the magnet temperature.

A special circumstance for these tests, however, is that the air conditioner return vents, shown in the figure to the left of the SXU near the floor, might cause more convective cooling compared to the situation in the tunnel. Thus the SXU beam pipe and magnet temperatures we measure for this note might be lower than the respective temperatures in the tunnel.

The tests performed on the SXU were the same tests that were performed on the HXU. The setup is very similar to the HXU setup. One change, however, is that the control parameters for the water heater were adjusted. There were rapid ± 0.1 °C water temperature variations when testing the HXU. These fluctuations had only a small effect on the magnet temperature since they happened quickly, however, it seemed possible to reduce them. A

Figure 2: Experimental setup showing the undulator with the thermistor connections near the gap which measure the beam pipe and magnet temperatures.

new program was written to model the water temperature control system. The software showed that by filtering the feedback water temperature, the controller was more stable and the derivative control term was not needed. One will see in the plots below that the beam pipe water temperature fluctuations are greatly reduced. The new controller parameters are $T_{PB} = 0.5$ °C, $\Gamma_I = 10$ sec, $\Gamma_D = 0$ sec, and the filter for the water temperature measurement has a time constant $\Gamma_{filter} = 5$ sec.

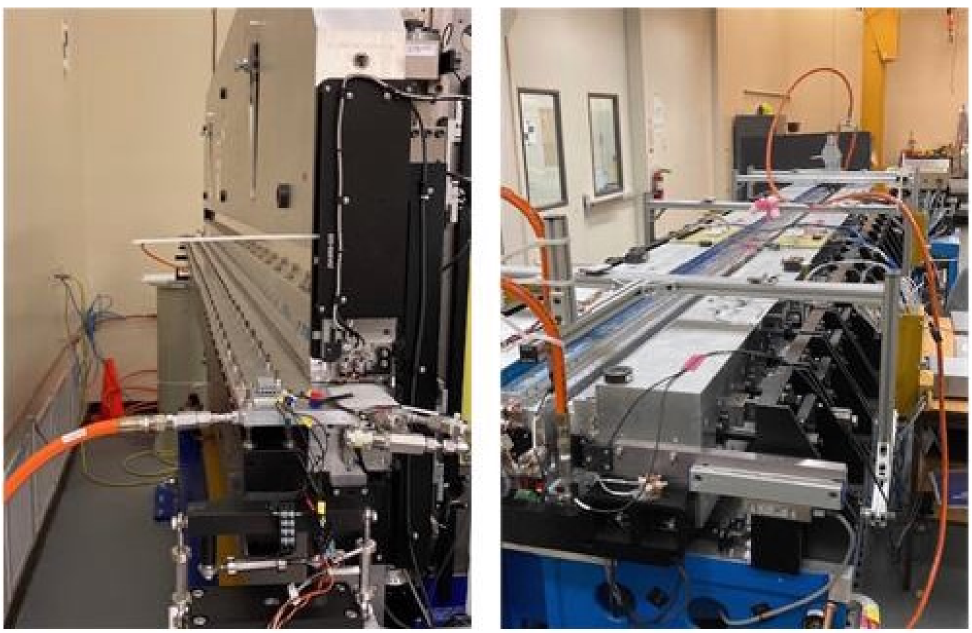

Figure 3: The SXU beam pipe (left) is exposed to air for convective cooling. The HXU beam pipe (right) is enclosed by the magnet jaws and spring cages limiting air cooling.

3 Test Results

3.1 The Need For Water Cooling

In this test we see what would happen if the high repetition rate beam was sent to the LCLS-II SXR undulators without the water cooling system installed. For this test, there was no water flow in the beam pipe. A current of 5 Amps was turned on in both of the corrector circuits for three days as the beam pipe and undulator temperatures were monitored, and then the current was turned off and the temperature was monitored for one day as the beam pipe and undulator cooled off. The HXU test similarly used 5 Amps. The currents and voltages on the trim windings were monitored and the power into the trims was calculated. The input power profile is shown in figure 4. The input power using the measured voltage and current when the trim windings were turned on was 16 W. The calculated power based on the resistance of the 20 gauge wire is 14.5 W. The difference is likely explained by the small resistance of the connections which increase the measured voltage. The SXU beam pipe is 3.8 m long and there is 0.25 m of corrector coil wire at each end. (There is extra wire at the ends because we used a prototype beam pipe for the tests.) The total length of each of the four wires in the corrector is 4.3 m. The power per unit length, using the 14.5 W total power divided by the 4.3 m length of each of the four wires, is 3.37 W/m. This is very close to the 3.3 W/m that the SXU will see.[3]

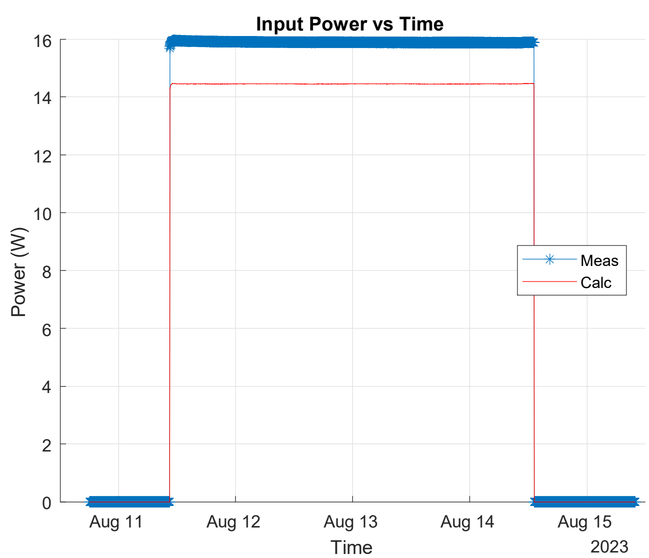

Figure 4: Power into the beam pipe trim windings. There was no water flowing in the beam pipe.

With power applied to the beam pipe and no water cooling, the temperature changes of the beam pipe, magnets, magnet keepers, and the air are shown in figure 5. Horizontal

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

dashed lines are drawn to aid in determining the temperature changes given the fluctuations in air temperature. The bottom line at -0.07 °C is meant to give the baseline that the changes are measured relative to. The middle line at 0.27 °C gives a magnet temperature rise relative to the baseline of 0.34 °C. The upper line at 0.75 °C gives a beam pipe temperature rise relative to the baseline of 0.82 °C. The undulator gap was 7.2 mm.

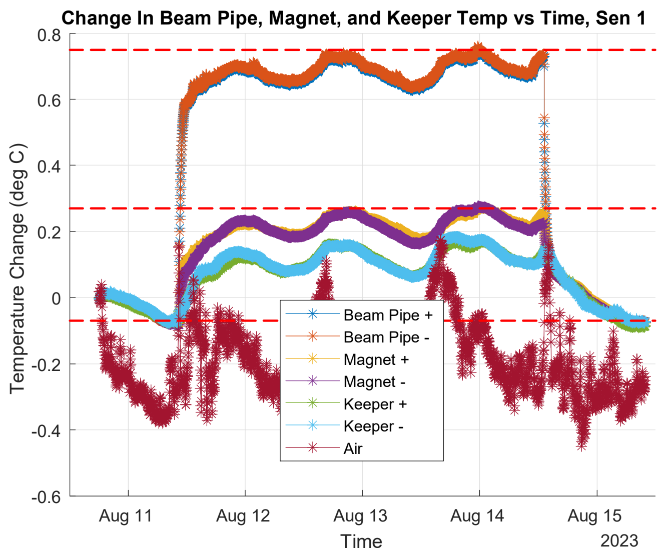

Figure 5: Magnet temperature rise with no water cooling of the beam pipe.

From these results, we conclude that if water cooling of the beam pipes is not implemented, the magnet temperatures will change by about 0.34 °C at small gap as the high repetition rate beam is turned on. This is above the 0.1 °C level where the K value changes by 10^{-4}.

Increasing the magnet temperature at small gap will lead to errors in the temperature corrections of the K value which are done in the tunnel. The magnet temperature measurement in the tunnel is made by temperature sensors placed on the outside of the magnet keepers. These temperature measurements are used to correct the K value. Temperature gradients, however, cause a difference between the magnet and keeper temperatures. As the gap changes, there will be a time dependent difference between the measured temperature on the keeper and the actual magnet temperature. The corrections using the measured keeper temperature will be in error.

A second measurement was made with 7 A in the beam pipe correctors. This was done to check the dependence of magnet temperature rise on beam pipe power in case the power per unit length into the beam pipe is larger than the estimated 3.3 W/m. The gap was again 7.2 mm. With 7 A in the corrector coils, the input power to the beam pipe correctors was 29.7 W. The power per unit length into the 4.3 m long corrector wires was 6.91 W/m. This is a factor of 2.05 larger than the 3.37 W/m of the 5 A measurement. The temperature changes of the beam pipe, magnets, magnet keepers, and the air are shown in figure 6. One notices that the magnets above (yellow trace) and below (purple trace)

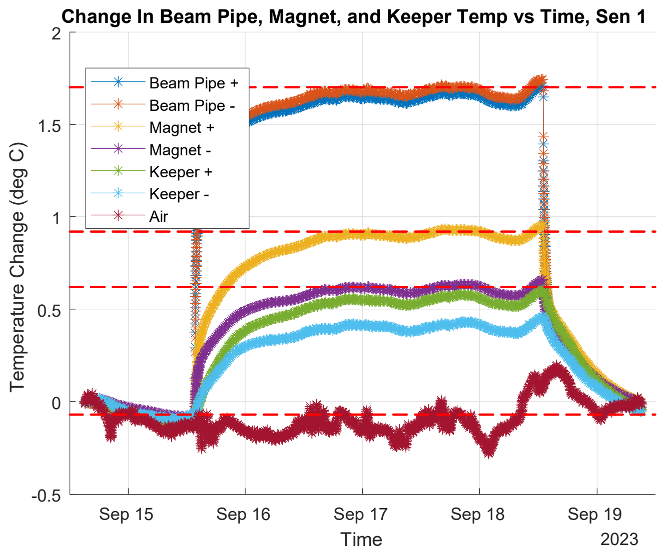

Figure 6: Magnet temperature rise with no water cooling of the beam pipe and 7 A applied to the beam pipe correctors.

the beam pipe are at different temperatures. The undulator had been used for other tests after the previous 5 A measurement and the undulator midplane was likely not centered on the beam pipe.[4] Horizontal dashed lines are again drawn to aid in determining the temperature changes given the fluctuations in air temperature. The bottom line at -0.07 °C is meant to give the baseline that the changes are measured relative to. The middle line through the purple trace at 0.62 °C gives a magnet temperature rise relative to the baseline of 0.69 °C. The middle line through the yellow trace at 0.92 °C gives a magnet temperature rise relative to the baseline of 0.99 °C. Averaging the upper and lower magnet temperatures gives an average magnet temperature rise of 0.84 °C. This is a factor of 2.47 above the 0.34 °C magnet temperature rise with 5 A applied. The upper line at 1.70 °C gives a beam pipe temperature rise relative to the baseline of 1.77 °C. This is a factor of 2.16 above the 0.82 °C beam pipe temperature rise with 5 A applied. We conclude that the beam pipe and magnet temperatures scale approximately linearly with applied power to the beam pipe, and that the magnet temperatures depend sensitively on the position of the undulator midplane relative to the beam pipe.

[4] The midplane position of the SXR undulators is not controlled in the MMF. The beam pipe was centered in the gap at large gap by an alignment crew. The undulator midplane shifts as the gap is closed due to compliance in the drive system. A nominal correction to account for the midplane shift was applied, but a centering error remained. This problem is being address in the LCLS-II-HE project. For a discussion, see Z. Wolf, "HE-SXU Midplane Position Errors And Corrections", LCLS-TN-22-8, October, 2022.

3.2 Water Temperature Controller Performance

For this test, the undulator gap was set to 100 mm. The water flow rate was 1.8 gpm. The chiller was set to 19.0 °C. The heated water temperature was set to the air temperature. The water temperatures shown in figure 7 were measured. The heated water temperatures (blue and yellow) followed the air temperature (purple). The input water temperature from the chiller (red) was constant on average. The heated water temperature had fluctuations of ±0.05 °C, but these are similar to the fluctuations in the supply temperature which the heater controller is not fast enough to reduce. These small, rapid fluctuations would not affect the undulator performance. In summary, the system heats the constant temperature input water to the local ambient air temperature, as it was designed to do.

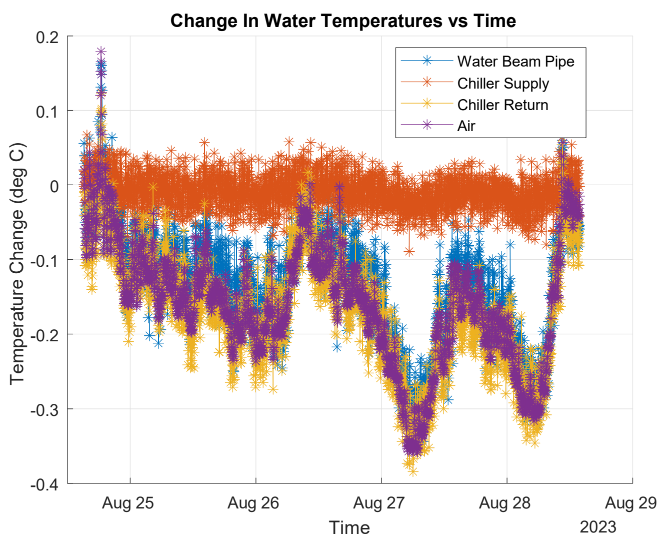

Figure 7: The controller keeps the beam pipe water temperature at the air temperature.

3.3 Stability Of The System With Disturbances

For these tests, a number of parameters were changed one at a time. Each test started in the baseline configuration with the undulator gap set to 7.2 mm. The water flow rate was 1.8 gpm. The chiller was set to 19.0 °C. The PID parameters were set to $T_{PB} = 0.5$ °C, $\Gamma_I = 10$ sec, $\Gamma_D = 0$ sec, and $\Gamma_{filter} = 5$ sec. The baseline current in the beam pipe correctors was 0 A. A parameter was changed for a period of time, and then the system was returned to the baseline configuration. The temperatures were monitored with a sampling time of 60 sec.

3.3.1 Change The Power In The Beam Pipe Correctors

Figure 8 shows the water temperatures as the beam pipe correctors are powered with 5 A in each circuit putting 14.5 W into the beam pipe correctors during the time between the vertical red dashed lines. At the left dashed line, the power in the beam pipe corrector

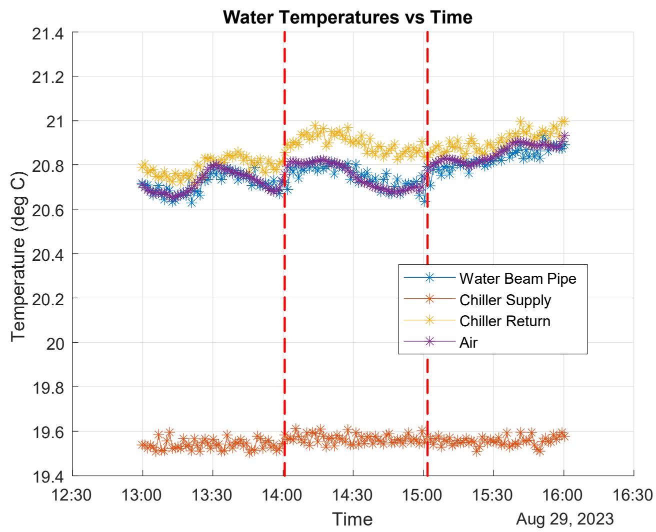

Figure 8: Water temperatures when 5A was put into the beam pipe correctors between the vertical red dashed lines.

is increased from 0 W to 14.5 W in a stepwise fashion. The power stays at 14.5 W until the right vertical dashed line. After the right dashed line the system goes back to the baseline configuration with 0 W. Note that these sensors use nominal calibrations from the manufacturer and there are offset errors in each sensor. The chiller also has an offset error. The red trace shows that the input water from the chiller was at constant temperature. The blue and purple traces show that the heated water temperature follows the air temperature changes. The yellow trace shows that the return water from the beam pipe is slightly heated when the power is on. The separation between the yellow and blue traces when the power is turned on increases by roughly 0.05 °C.

The expected temperature rise of the water can be calculated. The water flow is 1.8 gpm. The power going into the beam pipe correctors is 14.5 W, but the corrector wires are 0.5 m longer than the 3.8 m long beam pipe. The power going into the beam pipe is 14.5 W * 3.8 m / 4.3 m = 12.8 W. The calculated water temperature rise for a flow of 1.8 gpm and a power input of 12.8 W is 0.03 °C. This is in line with the rough temperature rise estimated from the plot.

3.3.2 Change The Water Flow

Figure 9 shows the effect of changing the water flow. The system is in the baseline con-

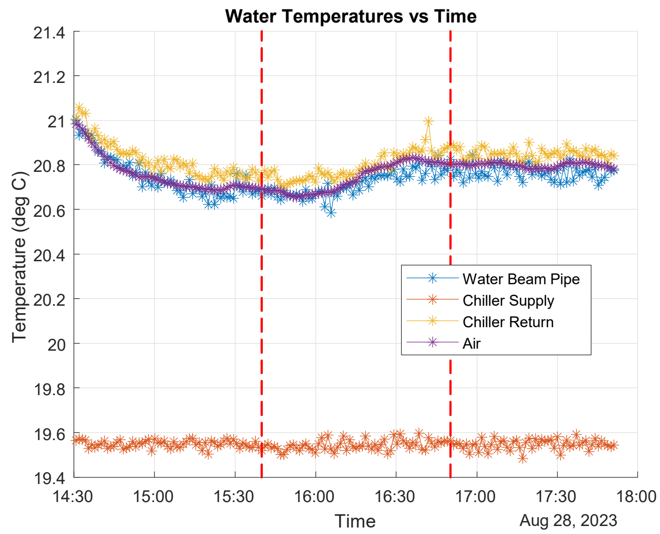

Figure 9: The flow was reduced from 1.8 gpm to 1.6 gpm in stepwise fashion between the dashed lines. The control system compensated so that no effect is noticible.

figuration up to the left vertical dashed line. At the left vertical dashed line, the flow is reduced from 1.8 gpm to 1.6 gpm in a stepwise fashion. The flow stays at 1.6 gpm until the right vertical dashed line. At the right vertical dashed line, the system goes back to the baseline configuration with 1.8 gpm. The purple, blue, and yellow traces show the air, heated water out, and return water temperatures, respectively. The input chilled water temperature stayed constant. There is no observable effect of the 11% flow reduction. The controller compensates for the reduced flow.

3.3.3 Change In Chilled Water Temperature

Figure 10 shows the effect of changing the chilled water temperature. The system is in

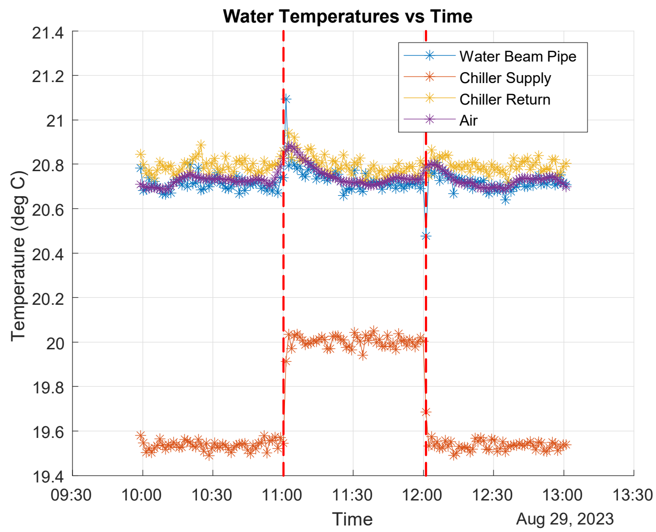

Figure 10: The chilled water supply temperature was increased by 0.5 °C between the vertical lines. The controller kept the heated water at the air temperature.

the baseline configuration up to the left vertical dashed line. At the left dashed line the chilled water temperature changes from 19.0 °C to 19.5 °C as indicated on the chiller. The chiller has an offset error in the water temperature, however, the temperature change seems accurate. The chilled water temperature stays at 19.5 °C, as indicated on the chiller, until the right dashed line. At the right vertical dashed line, the system goes back to the baseline configuration. The purple, blue, and yellow points show the air, heated water, and water return temperatures, respectively. There is no noticeable deviation of the heated water temperature from the air temperature. The controller compensated for the input chilled water temperature change. There is a change in air temperature at the dashed lines, probably caused by changes in the heat that the chiller put into the air in proximity to the air temperature sensor.

3.3.4 Open The Undulator Gap

Figure 11 shows the effect of opening the undulator gap. The system is in the baseline

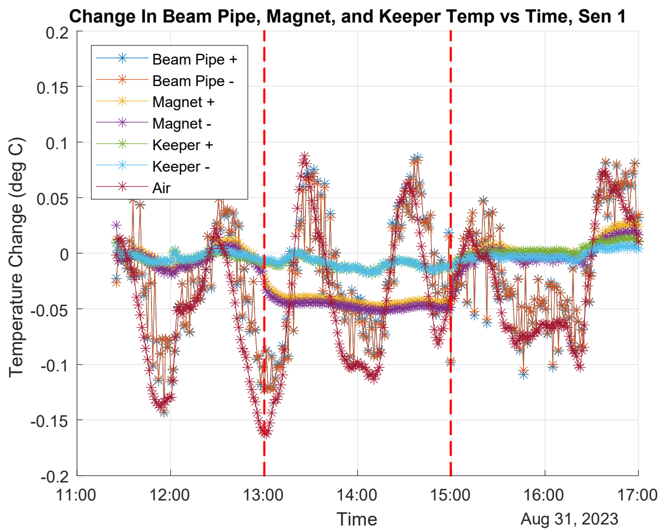

Figure 11: The undulator gap was opened from 7.2 mm to 25 mm between the vertical dashed lines. The magnet temperatures changed by 0.05 °C.

configuration up to the left vertical dashed line. Between the two dashed lines, the gap is at 25.0 mm. The system is back in the baseline configuration with the gap at 7.2 mm after the right dashed line. There is a 0.05 °C shift in the temperature of the purple and yellow curves giving the magnet temperature. This is below the 0.1 °C tolerance, but the cause must be investigated.

The air temperature sensor was near the end of the undulator next to the water system. These components expend energy and locally heat the air. The controller sets the water temperature to the air temperature, which was locally heated by the chiller and water heater. This was verified when the air temperature sensor was moved next to the sensors measuring the magnet temperature as shown in figure 12. The air temperature reference sensor and the air temperature monitoring sensor are shown in the left of the figure. They have a thermal mass and are wrapped in insulation to filter out rapid temperature variations. The package is held together with the red tape visible in the figure.

The test of opening the gap from 7.2 mm to 25 mm was repeated with the air temperature sensors near the magnet temperature sensors. The results are shown in figure 13. In this case, the purple and yellow curves giving the magnet temperatures show essentially no change. This shows the importance of placing the air temperature reference sensor in a location where it monitors the air temperature near the undulator magnets. Otherwise, the beam pipe water temperature will be different than the air temperature that the magnets see when the gap is opened.

Figure 12: The air temperature reference sensor and monitoring sensor were moved near the thermistors measuring the magnet temperatures.

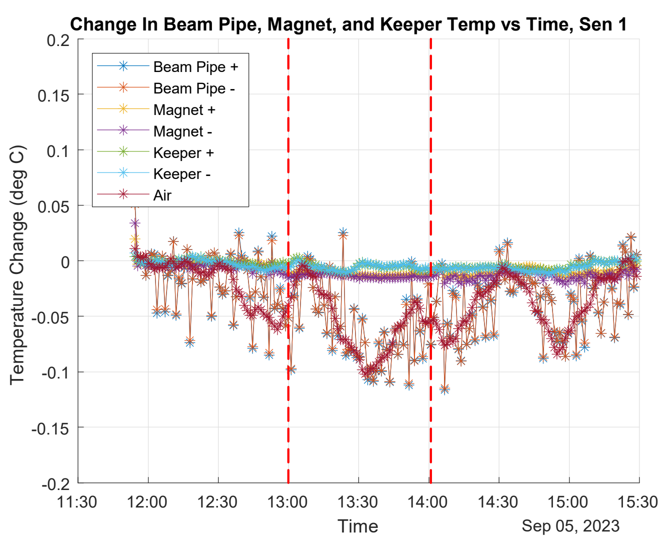

Figure 13: The gap was opened from 7.2 mm to 25 mm during the time between the vertical dashed lines. The magnet temperatures did not change.

4 Conclusion

Water cooling is required for the LCLS-II undulator beam pipes when the beam repetition rate is increased with the superconducting linac. In this note a proposed solution for cooling the beam pipes was tested on an SXR undulator. A system was presented which heated chilled water to the ambient temperature. The water temperature was demonstrated to follow the air temperature. Disturbances to the system parameters were introduced and it was demonstrated that the controller compensated adequately for the disturbances. When the beam pipe is at the air temperature, the undulator gap can be changed without an effect on the magnet temperature since the magnets are always in the same temperature environment.