Tests Of A Proposed Undulator Beam Pipe Cooling Method

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Abstract  
The LCLS-II SXR and HXR beam pipes will have an increased heat load from the high repetition rate beam of the superconducting linac. In addition, the beam pipes have embedded corrector windings which produce heat. Water cooling channels are incorporated in the beam pipes. They have so far not been used, but are expected to be required with the high repetition rate beam. The water cooling must keep the beam pipe at the local ambient temperature so that the undulator magnets are not affected by the beam pipe temperature. In this note tests are presented to show that locally heating chilled water to ambient temperature is a viable way to provide the required beam pipe temperature regulation.

1 Introduction

The LCLS-II superconducting linac will increase the pulse repetition rate from the present 120 Hz to 1 MHz. This will increase the heating of the beam pipe from the image currents and from spontaneous radiation. In addition, the beam pipe has embedded Earth field corrector coils which produce heat. Without intervention, the temperature of the beam pipe will change depending on beam conditions, corrector currents, and undulator gap.

If the beam pipe temperature is different than the ambient temperature, the undulator magnet temperatures will change as the gap is changed. Local heating from the beam pipe can create temperature gradients in the magnets making temperature corrections very difficult. As a general rule, the relative change in the remnant field of the magnets is $10^{-3}$ per degree Celsius. We wish to keep the magnetic fields in the undulator accurate at the $10^{-4}$ level. This necessitates eliminating temperature gradients and accurately knowing the magnet temperature to approximately 0.1 deg C. As will be demonstrated, water cooling of the beam pipe is required to keep the beam pipe at ambient temperature allowing accurate magnet temperature determination.

The water cooling system must maintain temperature regulation in spite of input water temperature fluctuations and flow fluctuations, varying undulator gaps, varying beam currents, and varying corrector currents. Keeping the beam pipe temperature constant under varying conditions requires a control system for the cooling water. In this note, a study is made of the beam pipe water cooling system and a prototype system is described which demonstrates a solution to the temperature control problem.

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2 Beam Pipe Water Cooling System Parameters

A cross section of the HXR beam pipe is shown in figure 1.\textsuperscript{2} The central chamber is evacuated for the electron beam. The neighboring chambers on either side are for water cooling. The four square grooves around the central chamber are for the Earth field corrector windings. The SXR beam pipe cross section is very similar.

![Figure 1: Cross section of the HXR beam pipe.](image)

A detailed study of the beam pipe design is given in an Engineering Report from APS.\textsuperscript{3} Some results from the report relevant to these tests are the following:

1. The beam pipe was designed to mitigate a 3.3 W/m heat load with a temperature rise below 0.1 deg C. The 3.3 W/m consisted of 2.55 W/m from the beam and 0.75 W/m from the Earth field correctors.

2. The water flow in the two cooling channels should be routed in parallel.

3. The water flow should be restricted to between 0.77 gpm and 1.05 gpm in each of the two channels. The total flow of the parallel combination should be between 1.54 gpm and 2.10 gpm. This restriction is in order to meet the cooling requirements but not lead to erosion of the aluminum chambers.

4. The maximum pressure drop for each channel is calculated to be 20.5 psi at 1.05 gpm.

As part of the tests for this note, we wish to experimentally verify these values. The conditions in the tunnel are documented in a Room Data Sheet.\textsuperscript{4} The results relevant to this test are the following:

1. The ambient tunnel temperature is 20 ± 1 deg C. The temperature starts at approximately 19 deg C at the upstream end, is heated by equipment in the tunnel, and the temperature at the downstream end is approximately 21 deg C.

\textsuperscript{2}J. Lerch, et. al., "Design Of The HGVPU Undulator Vacuum Chamber For LCLS-II", Proceedings Of NAPAC2016, Chicago, IL.

\textsuperscript{3}J. Carter, "Thermal and pressure drop analyses for the SXRU and HGVPU undulator vacuum chambers", APS 1692817, January, 2016.

2. The temperature of the cooling water for the beam pipes is $20 \pm 0.5$ deg C. (This will need to be changed. See the following paragraph.)

3. The water pressure was not specified, but the requirement of supplying 1.75 gpm to 53 chambers with the dimensions given above was specified.

One expects that the mean temperature of the cooling water can be changed, in particular that it can be lowered 1 °C below the Room Data Sheet value so that the water is at the minimum tunnel temperature. This will be required if the control system heats the water to ambient temperature. The specified 0.5 deg C variation in cooling water temperature must be accounted for in a control system since we require stability at the local ambient temperature.

At small undulator gaps, the air between the beam pipe and the undulator magnets is no longer an insulator.\textsuperscript{5} This effect has been previously studied.\textsuperscript{6} This study was done in a room without tight temperature control, yet it demonstrated the coupling between beam pipe temperature and undulator magnet temperature. For this note, these measurements will be repeated and many others performed in a room with fairly good temperature control so that an accurate determination of the temperature coupling between the beam pipe and the magnets can be made.

3 \hspace{1cm} \textbf{Requirements}

The LCLS-II undulator requirements come from a Physics Requirements Document.\textsuperscript{7} The requirements related 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, but the beam pipe temperature will have the maximum effect on the magnets at the smallest gap.

2. The accuracy for setting the undulator $K$ value is $\Delta K/K = 3.0 \times 10^{-4}$ for the SXR line and $2.3 \times 10^{-4}$ 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 variations below $\Delta K/K = 1 \times 10^{-4}$.

4 \hspace{1cm} \textbf{Experimental Setup}

The tests for this note were performed in the assembly area of the MMF. The temperature in this area is nominally stable to $\pm 0.25$ deg C. If necessary, further measurements can be made in the undulator calibration laboratory where the temperature is stable to 0.1 deg C, however, extra care must be taken in the calibration laboratory so that any water leaks do not wet the high precision granite measurement benches.

\textsuperscript{5}H. Wang, "Undulator vacuum chamber and magnets thermal studies", Unpublished, July, 2018.
The water system setup for the test is illustrated in figure 2. A laboratory chiller (BV Thermal Systems model MC025-C1) supplies chilled water at a temperature under operator control. A flow control valve on the chiller allows the total flow of water in the beam pipe to be adjusted. A control system (details below) takes input from various sensors and sets the temperature of the water at the input to the beam pipe. The purpose of the control system is to make the water temperature equal to the local ambient temperature. Flow sensors F1 and F2 (Dwyer Instruments model VFB-85-SSV) measure the flow in each channel of the beam pipe. The flow sensors also have valves to adjust the flow in each channel individually. Pressure sensors P1 to P4 (Dwyer Instruments model SGY-D10522N) measure the input and output water pressure for each channel of the beam pipe. Temperature sensors T1 to T4 (Keysight model 34308A 10 K thermistors) measure the input and output water temperatures for each water channel of the beam pipe. Temperature sensors Tm represent a number of small sensors that measure the magnet temperatures in the recess of the magnets below the poles. Details of these measurements are given below. Temperature sensors Tb represent a number of sensors that measure the temperature of the beam pipe in the magnet recesses. Details of these measurements are given below. Temperature sensors Ta represent a number of sensors that measure the ambient temperature and the temperature of the magnet keepers and strongbacks (Keysight model 34308A 10 K thermistors).

Figure 2: Schematic of the water system instrumentation for the test.

Measuring the magnet and beam pipe temperatures requires some care because of the limited space available. Figure 3 shows the beam pipe in the undulator gap at the minimum gap of 7.2 mm. At 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 0.75 mm. Four small thermistors were placed in the recess between the beam pipe and the magnets: two thermistors were placed on the beam pipe on either side of the gap, and two thermistors were placed on the magnets on either side of the gap. The thermistors (Simitec model 223F13122-07U015) are 0.3 mm in diameter and were placed in contact with the beam pipe and magnets using thermal paste (Arctic type MX-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 4. 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 (Keysight model 34970A with a 34901A multiplexer card) was used to measure the resistance of the thermistors and a calibration supplied by the manufacturer was applied to determine the temperature. As a check, a second set of four thermistors was also installed. These thermistors were of a different type (Semitec model 103J1-050). They are more rugged thin film thermistors and are 0.5 mm thick. They come with a nominal calibration from the manufacturer. Because of their larger size, they stick into the air gap further and are considered a check rather than the primary measurement. In general, both sets of sensors agreed well.

Various systems have been proposed to control the water temperature. For example, an open loop heat exchanger near each undulator might bring the input water temperature to the ambient temperature. Alternatively, heating incoming water to ambient temperature has been successfully used in the past. More complicated systems that mix hot and cold water are used in the MMF to control the laboratory temperature. For these tests, the chosen method is to bring in water at a low temperature and heat it to the local ambient temperature. The heater used is an in-line unit (Watlow Fluent model 2193-1868). The heater uses 120 VAC and can put 1000 W into the water. It is a larger unit (1.625 inch O.D. by 6.5 inches long) without a baffle, so it can handle 2 gpm flow with 2 psi pressure drop. The 120 VAC supplied to the heater is pulse width modulated (PWM) to adjust the power level. The PWM signal is sent from the controller to a solid state relay (Watlow model DA10-24C0-0000) which turns the 120 VAC on at 10 Hz for a varying length of time depending on the desired average power level. The controller (Watlow model PM Plus PM6J2CJ-1PAAVWP) uses the difference between two thermistor inputs to set the PWM level. The reference sensor measures the local ambient temperature and the feedback sensor measures the water temperature output from the heater. The controller measures the two thermistors every 0.1 sec. Since the heated water temperature is measured near the heater, there is minimal delay in the system, which minimizes the chance of oscillation. Short water lines go to the beam pipe so there is minimal temperature change, especially since the lines are at ambient air temperature. The water heater is interlocked both by a flow switch (McMaster-Carr part number 42015K2) set to 0.5 gpm and by a signal from the chiller that it is operating normally. When the interlock conditions are met, the system turns on a solid state relay (McMaster-Carr part number 7456K22) which is in the heater circuit.

Power is put into the beam pipe by running current through the four wires that make up the Earth field corrector. Various input powers, accounting for both the corrector currents and the beam heating, can be tested by adjusting the current in the wires. The power is measured by measuring the voltage and current in each circuit. The power supplies (Kepco model BOP5-20) are set and read by a USB data acquisition unit (National Instruments USB-6216). The beam pipe corrector power system is illustrated in figure 5.

Three different undulators were used for the tests depending on availability. Initial setups and measurements were done on HXU-016. The measurements demonstrating the need for beam pipe water cooling were done on HXU-000. All other measurements were done on HXU-011. Although the undulators used for these tests were HXR undulators,

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Figure 5: Schematic of the system used to heat the beam pipe.

we expect the results will apply also to SXR undulators since, as we will see, the beam pipe temperature control problem is basically a problem of controlling the input water temperature.

Figure 6 shows HXU-011 under test. The small thermistors are at the ends of the wires going into the 7.2 mm gap in the center of the undulator. These thermistors attached to the beam pipe and magnets are shown in figure 7. Above the small thermistors are two thermistors attached to approximately 5 g of aluminum acting as a thermal mass and insulated with 1 cm thick plastic foam. One sensor measures the air temperature for the measurement system. The other sensor measures the air temperature for the water heater controller. The purpose of the thermal mass and insulation is to reduce rapid air temperature fluctuations. The air temperature sensors were initially placed toward the side of the undulator, but there is an approximate 0.05 °C temperature gradient between the side of the undulator and the center of the gap necessitating moving the sensors to the gap. One also sees the wires powering the corrector windings on the near side of the left strongback. One the right strongback are two cables for thermistors measuring the input water temperature to the upper and lower water channels of the beam pipe. The water connections are temporary while we wait for the stainless steel tubing going from the beam pipe up to elevated water hoses. The stainless steel tubes will be strain relieved to the aluminum extrusions crossing the undulator in a manner similar to what is shown. The extrusions are in place in the tunnel to hold the top cover of the undulator.

Figure 8 shows the water system. The chiller is on the right. The flow meters and pressure gauges are on the upper part of the rack on the left. The controller is the small panel in the center. The heater, interlocks, and plumbing are on the back side of the rack and are shown in a photo later in the note.
Figure 6: HXU-011 under test.
Figure 7: Small thermistors are attached to the beam pipe and magnets.

Figure 8: The water heater and flow controls are in the rack on the left. The chiller is on the right.
5 Analysis Of The Beam Pipe Temperature Control System

5.1 Heating The Water As It Flows In The Beam Pipe

According to the APS Engineering Report\(^9\) mentioned above, the beam plus the corrector windings put 3.3 W/m into the beam pipe. Suppose this energy goes into the water flowing in the beam pipe. How much does the water temperature rise as it flows through the beam pipe?

Consider a volume of water $\Delta V = A \Delta x$, where $A$ is the area of the water chambers in the beam pipe and $\Delta x$ is a segment along its length. Following this segment, the temperature rise $dT$ in time $dt$ is given by

$$P_L \Delta x dt = C \rho \Delta V dT$$

where $P_L$ is the power per unit length put into the beam pipe, $C$ is the specific heat of water $4.19 \times 10^3$ J/kg/°C, and $\rho$ is the mass density of water 997 kg/m\(^3\). Integrating for time $L/v$, where $L$ is the length of the beam pipe and $v$ is the velocity of the water, we find

$$P_L \Delta x \frac{L}{v} = C \rho A \Delta x \Delta T$$

where $\Delta T$ is the temperature rise of the water as it flows through the entire beam pipe. Letting $F = Av$ be the volumetric flow rate, and $P = P_L L$ be the total power put into the beam pipe, we find

$$P = C \rho F \Delta T$$

Using a median total flow rate from the ANL Engineering Report, $F = 1.75$ gpm = $1.10 \times 10^{-4}$ m\(^3\)/s, and total power into a 4 meter long beam pipe $P = (3.3 \text{ W/m})(4 \text{ m}) = 13.2$ W, we find

$$\Delta T = \frac{P}{C \rho F}$$

$$= \frac{13.2 \text{ W}}{(4.19 \times 10^3 \text{ J/kg/°C}) \cdot (997 \text{ kg/m}^3) \cdot (1.10 \times 10^{-4} \text{ m}^3/\text{s})}$$

$$= 0.029 \text{ °C}$$

This is an important result. It says that we can basically ignore the temperature rise of the water as it flows through the beam pipe. The problem of controlling the beam pipe temperature is a problem of controlling the temperature of the water going into the beam pipe.

5.2 Heating The Water Going Into The Beam Pipe

According to the Room Data Sheet\(^10\) mentioned above, the tunnel temperature varies from 19 °C to 21 °C. If the water going into the tunnel is at 19 °C and we want to heat it to the

\(^9\)J. Carter, "Thermal and pressure drop analyses for the SXRU and HGVP1 undulator vacuum chambers", APS_1692817, January, 2016.
local ambient temperature, then the heater must be able to heat the water by 2 °C. Using $F = 1.75 \text{ gpm} = 1.10 \times 10^{-4} \text{ m}^3/\text{s}$ given above, the power the heater must supply is

$$P = C \rho F \Delta T$$

$$= (4.19 \times 10^3 \text{ J/kg/°C}) \left( 997 \text{ kg/m}^3 \right) (1.10 \times 10^{-4} \text{ m}^3/\text{s}) (2 \text{ °C})$$

$$= 919 \text{ W}$$

We choose a 1 kW heater for the control system.

### 5.3 Controlling The Water Temperature

In this section we make a model of the water heater and the controller. In practice, delays, nonlinearities in the controller response due to its proportional band, and the discrete time nature of the controller make the system more complicated than presented here. The simple model, however, provides a good starting point for setting the PID parameters and provides an understanding of how the PID parameter values affect the system performance.

Consider the control system shown in figure 9. The input power to the heater is $P$

![Figure 9: Schematic of the beam pipe water temperature control system.](image)

and it raises the water temperature from $T_{in}$ to $T_{out}$. The controller monitors $T_{out}$ and it adjusts $P$ to make $T_{out}$ equal to a reference temperature $T_{ref}$.

The energy balance equation governing the heater is

$$P + C \rho F (T_{in} - T_{out}) = C \rho V \frac{dT_{out}}{dt}$$

where $V$ is the volume of water in the heater. We assume the water goes into the volume $V$ carrying energy per unit time $C \rho F (T_{in} - T_0)$ relative to a reference energy flow at $T_0$, is well mixed with power $P$ added, and leaves carrying energy per unit time $C \rho F (T_{out} - T_0)$.  

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The remaining energy per unit time heats the water in $V$ according to $C \rho V \frac{dT_{out}}{dt}$. We can rewrite the energy balance equation as

$$P = C \rho F \left( T_{out} - T_{in} + \frac{V}{F} \frac{dT_{out}}{dt} \right) \quad (11)$$

The water flow rate may have some variation.

$$F = \bar{F} + \delta F \quad (12)$$

where $\bar{F}$ is the average flow rate and $\delta F$ is the fluctuation, which is considered small compared to the average. Similarly, the input water temperature may have some variation.

$$T_{in} = \bar{T}_{in} + \delta T_{in} \quad (13)$$

where $\bar{T}_{in}$ is the average input water temperature and $\delta T_{in}$ is the fluctuation, which is considered small compared to the average. In this case, the equation governing the heater is

$$P = C \rho \left( \bar{F} + \delta F \right) \left( T_{out} - \bar{T}_{in} - \delta T_{in} + \frac{V}{\bar{F}} \frac{dT_{out}}{dt} \right) \quad (14)$$

We assume $dT_{out}/dt$ is small and use the average flow in the last expression. We now linearize this equation keeping only first order terms in small quantities.

$$P = C \rho \bar{F} \left[ (T_{out} - \bar{T}_{in}) + \frac{V}{\bar{F}} \frac{dT_{out}}{dt} + \frac{\delta F}{\bar{F}} (T_{out} - \bar{T}_{in}) - \delta T_{in} \right] \quad (15)$$

In the flow fluctuation term we used the average $T_{out}$ since we are working to first order in small quantities. This is the equation governing the heater, and we next consider the controller.

We use a PID controller, but we assume slow dynamics so that a derivative term is not needed. The PI controller adjusts the heater power according to

$$P = K_P (T_{ref} - T_{out}) + K_I \int (T_{ref} - T_{out}) dt \quad (16)$$

where $K_P$ and $K_I$ are controller parameters. The controller equation can also be written as

$$P = K_P \left( (T_{ref} - \bar{T}_{in}) - (T_{out} - \bar{T}_{in}) \right) + K_I \int \left( (T_{ref} - \bar{T}_{in}) - (T_{out} - \bar{T}_{in}) \right) dt \quad (17)$$

Since all expressions in this equation involve temperatures relative to $\bar{T}_{in}$, and the heater equation is similarly expressed in terms of temperatures relative to $\bar{T}_{in}$, we redefine our temperatures to be relative to $\bar{T}_{in}$. We keep the same symbols, but any temperature $T$ in the equations will now represent $T - \bar{T}_{in}$ in standard temperature units. The heater and controller equations now become

$$P = C \rho \bar{F} \left( T_{out} + \frac{V}{\bar{F}} \frac{dT_{out}}{dt} + \frac{\delta F}{\bar{F}} (T_{out} - \bar{T}_{in}) \right) \quad (18)$$
\[ P = K_P (T_{ref} - T_{out}) + K_I \int (T_{ref} - T_{out}) \, dt \] (19)

The next step is to take the Laplace transform of both the heater and the controller equations. We don’t change the notation, but recognize that all variables are now the Laplace transform of the time domain variables. The Laplace transformed heater and controller equations are

\[ P = C_F \rho F \left[ \left( 1 + \frac{sV}{F} \right) T_{out} + \frac{\delta F}{F} T_{out} - \delta T_{in} \right] \] (20)

\[ P = \left( K_P + \frac{1}{s} K_I \right) (T_{ref} - T_{out}) \] (21)

To simplify the notation, define the heater parameter \( K_H \) by

\[ K_H = C_F \rho F \] (22)

Also, \( V/F \) is a heater time constant which we represent as

\[ \Gamma_H = \frac{V}{F} \] (23)

We define the transfer functions of the heater and controller, denoted to be \( G \) and \( K \) respectively, to be

\[ \frac{1}{G} = K_H (1 + s \Gamma_H) \] (24)

\[ K = \left( K_P + \frac{1}{s} K_I \right) \] (25)

The heater and controller equations are now

\[ P = \frac{1}{G} T_{out} + K_H \left( \frac{\delta F}{F} T_{out} - \delta T_{in} \right) \] (26)

\[ P = K (T_{ref} - T_{out}) \] (27)

Combining the heater and controller equations, we now have

\[ \frac{1}{G} T_{out} + K_H \left( \frac{\delta F}{F} T_{out} - \delta T_{in} \right) = K (T_{ref} - T_{out}) \] (28)

We solve this equation for \( T_{out} \).

\[ T_{out} \left( 1 + GK \right) = GKT_{ref} + GKH \left( -\frac{\delta F}{F} T_{out} + \delta T_{in} \right) \] (29)

\[ T_{out} = \frac{GK}{(1 + GK)} T_{ref} + \frac{GKH}{(1 + GK)} \left( \delta T_{in} - \frac{\delta F}{F} T_{out} \right) \] (30)

This is a standard form for feedback systems, including systems with disturbances. From these equations, we see that the strategy for controlling the water temperature is to make
$GK$ large so that $T_{out} \simeq T_{ref}$, and to make $K_H/K$ small so the term with the fluctuations is small. 

The controller has industry standard ways of defining $K_P$ and $K_I$. It defines $K_P = P_{max}/T_{PB}$, where $P_{max}$ is the maximum heater power, 1 kW, and $T_{PB}$ is the proportional band, the temperature range of the error $(T_{ref} - T_{out})$ over which the power goes from zero to $P_{max}$. The controller defines $K_I = K_P/\Gamma_I$, where $\Gamma_I$ is the "integration time". Using these definitions for $K_P$ and $K_I$, and after some lengthy algebra, we find

$$T_{out} = \frac{K_P}{K_H \Gamma_H} \left( \frac{s + \frac{1}{\Gamma_I}}{s^2 + \frac{1}{\Gamma_H} \left( 1 + \frac{K_P}{K_H} \right) S + \frac{K_P}{K_H} \frac{1}{\Gamma_H} \Gamma_I} \right) T_{ref}$$  

$$+ \frac{s}{\Gamma_H} \left( \frac{1}{s^2 + \frac{1}{\Gamma_H} \left( 1 + \frac{K_P}{K_H} \right) S + \frac{K_P}{K_H} \frac{1}{\Gamma_H} \Gamma_I} \right) \left( \delta T_{in} - \frac{\delta F}{F} T_{out} \right)$$

The poles are given by

$$p_{1,2} = \frac{1}{2} \left[ -\frac{1}{\Gamma_H} \left( 1 + \frac{K_P}{K_H} \right) \pm \sqrt{\left( \frac{1}{\Gamma_H} \left( 1 + \frac{K_P}{K_H} \right) \right)^2 - 4 \frac{K_P}{K_H} \frac{1}{\Gamma_H \Gamma_I}} \right]$$

In terms of $p_1$ and $p_2$, $T_{out}$ is given by

$$T_{out} = \frac{K_P}{K_H \Gamma_H} \frac{s + \frac{1}{\Gamma_I}}{(s - p_1)(s - p_2)} T_{ref} + \frac{s}{\Gamma_H} \frac{1}{(s - p_1)(s - p_2)} \left( \delta T_{in} - \frac{\delta F}{F} T_{out} \right)$$

Note that the poles have a negative real part so the system is stable. Also note that in order to avoid damped oscillations, the term under the square root must be positive.

$$\left( \frac{1}{\Gamma_H} \left( 1 + \frac{K_P}{K_H} \right) \right)^2 > 4 \frac{K_P}{K_H} \frac{1}{\Gamma_H \Gamma_I}$$

Solving for $\Gamma_I$, we find

$$\Gamma_I > 4 \frac{\Gamma_H}{\frac{K_P}{K_H} \left( 1 + \frac{K_P}{K_H} \right)^2}$$

This expression will be important when setting the controller parameters.

A couple interesting facts about $T_{out}$ are easily seen from its expression. First, suppose we only do proportional control. In this case $\Gamma_I \to \infty$. Then

$$T_{out} = \frac{K_P}{K_H \Gamma_H} \frac{1}{s + \frac{1}{\Gamma_H} \left( 1 + \frac{K_P}{K_H} \right)} T_{ref}$$

$$+ \frac{1}{\Gamma_H} \left( \frac{1}{s + \frac{1}{\Gamma_H} \left( 1 + \frac{K_P}{K_H} \right)} \right) \left( \delta T_{in} - \frac{\delta F}{F} T_{out} \right)$$

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After the transient from a step response, the output temperature settles to

\[
T_{out} = \frac{K_P}{K_H} \frac{T_{ref}}{1 + \frac{K_P}{K_H}} + \frac{1}{1 + \frac{K_P}{K_H}} \left( \frac{\delta T_{in} - \frac{\delta F}{F} T_{out}}{T_{ref}} \right)
\]  

(39)

The output temperature is not equal to the reference temperature. We need the integral term to correct this. The fluctuations are reduced by a factor of \(K_H/K_P\), as expected.

Another easily seen fact about \(T_{out}\) is that with the controller’s integral term, the steady state temperature after a step response is \(T_{ref}\). A step input has a Laplace transform that goes at \(1/s\). This makes a pole at \(s = 0\) in the first term with \(T_{ref}\), but the pole is cancelled by a zero in the second term. The steady state value in the time domain is found by setting \(s = 0\) in the expression for \(T_{out}\). This gives a steady state value of \(T_{out} = T_{ref}\). In more detail, consider a step input where \(T_{ref} = \frac{1}{s} T_{ref}^0\), \(\delta T_{in} = \frac{1}{s} \delta T_{in}^0\), and \(\delta F = \frac{1}{s} \delta F^0\). Taking the inverse Laplace transform of the expression for \(T_{out}\), we have

\[
T_{out}(t) = T_{ref}^0 + \frac{K_P}{K_H \Gamma_H p_1 (p_1 - p_2)} T_{ref}^0 e^{-p_1 t} + \frac{K_P}{K_H \Gamma_H p_2 (p_2 - p_1)} T_{ref}^0 e^{-p_2 t}
\]

(40)

\[
+ \frac{1}{\Gamma_H (p_1 - p_2)} \left( \frac{\delta T_{in}^0 - \frac{\delta F^0}{F} T_{out}}{T_{out}} \right) e^{-p_1 t}
\]

(41)

\[
+ \frac{1}{\Gamma_H (p_2 - p_1)} \left( \frac{\delta T_{in}^0 - \frac{\delta F^0}{F} T_{out}}{T_{out}} \right) e^{-p_2 t}
\]

(42)

where we used

\[
p_1 p_2 = \frac{K_P}{K_H \Gamma_H \Gamma_I}
\]

(43)

The step response settles to \(T_{ref}^0\) after the transient terms get small. In order to make the transient terms small, we need to make \(|p_1 - p_2|\) large. Using the expression for the poles, we find

\[
p_1 - p_2 = \sqrt{\left( \frac{1}{\Gamma_H \left( 1 + \frac{K_P}{K_H} \right)} \right)^2 - 4 \frac{K_P}{K_H \Gamma_H \Gamma_I}}
\]

(44)

In order to make \(p_1 - p_2\) large, we make \(\frac{K_P}{K_H}\) large.

We will confirm these findings using numerical simulations in a section below.

### 5.4 Values Of The PI Parameters

We wish to make \(K_P \gg K_H\) in order to reduce the effect of input water temperature and flow fluctuations. The definition of \(K_H\) was

\[
K_H = C \rho \overline{F}
\]

(46)

Putting in numerical values, we have

\[
K_H = (4.19 \times 10^3 \text{ J/kg/°C}) \left(997 \text{ kg/m}^3\right) \left(1.10 \times 10^{-4} \text{ m}^3/\text{s}\right)
\]

(47)

\[
= 460 \text{ W/°C}
\]

(48)
As a starting point, if we make $K_P$ five times as large,

$$K_P = 2300 \text{ W/°C}$$  \hspace{1cm} (49)

As we saw above,

$$K_P = \frac{P_{\text{max}}}{T_{PB}}$$  \hspace{1cm} (50)

where $T_{PB}$ is the temperature proportional band. Using $P_{\text{max}} = 1$ kW, we find

$$T_{PB} = 0.43 ^\circ \text{C}$$  \hspace{1cm} (51)

This number is entered into the controller using the front panel.

The value of $K_I$ affects the settling time of $T_{out}(t)$. We saw previously that in order to avoid oscillations, we need

$$\Gamma_I > 4\Gamma_H \frac{K_P}{K_H} \left( 1 + \frac{K_P}{K_H} \right)^2$$  \hspace{1cm} (52)

The value of $\Gamma_H$ is given by $V/F$. The volume of the heater is a cylinder. The manufacturer specifies that the heater watt density is 300 W/in$^2$ at 240 V, which is equivalent to 75 W/in$^2$ at 120 V. Since the heater power with 120 V is 1000 W, the area of the heater is 13.3 in$^2$, or $8.58 \times 10^{-3}$ m$^2$. The area of the heater is given by $A = 2\pi RL$, and the heater is 0.17 m long. The radius of the heater is then $R = 8.03 \times 10^{-3}$ m.

$$V = \pi \left( 8.03 \times 10^{-3} \text{ m} \right)^2 (0.17 \text{ m})$$  \hspace{1cm} (53)

$$= 3.44 \times 10^{-5} \text{ m}^3$$  \hspace{1cm} (54)

Since

$$\bar{F} = 1.10 \times 10^{-4} \text{ m}^3/s$$  \hspace{1cm} (55)

we have

$$\Gamma_H = \frac{V}{\bar{F}} = 0.31 \text{ sec}$$  \hspace{1cm} (56)

Therefore,

$$\Gamma_I > 4 (0.3 \text{ sec}) \frac{5}{(1 + 5)^2} = 0.17 \text{ sec}$$  \hspace{1cm} (57)

We choose

$$\Gamma_I = 1 \text{ sec}$$  \hspace{1cm} (58)

This value is also entered into the controller using the front panel.

5.5 **Numerical Model Of The System**

In practice, the temperature control system is more complicated than an analytical analysis can easily handle. For instance, when the difference in temperature between the reference and the output is outside the proportional band, the heater is either full on or off. The system is nonlinear. In addition, the controller can average its inputs in order to reduce noise. Does this averaging cause time delays and make the system oscillate? Is the time between samples that the digital controller takes small enough compared to the dynamics of
the system? In order to study such effects, a numerical model of the temperature control system was written. This was done by taking the analytical equations and discretizing them. The starting point is our first analytical equations in the time domain.

\[ P = K_p(T_{ref} - T_{out}) + K_I \int (T_{ref} - T_{out}) \, dt \]  

\[ P + C \rho F T_{in} - C \rho F T_{out} = C \rho V \frac{dT_{out}}{dt} \]  

To solve the equations, we use a small time step \( \delta t = 0.001 \) sec for the time base of the model. The controller updates every \( \Delta t = 0.1 \) sec, or every 100 steps of the model. Let \( i \) be the index giving the time in the model, \( t(i) = i \delta t \). Let \( k \) be the index of the controller sample, \( t_c(k) = k \Delta t \). We want the output temperature at time \( t(i) \) given all samples up to \( i \).

Suppose at time \( t(i) \), it is time for the controller to sample. In this case \( i \delta t = k \Delta t \), for some \( k \). The controller calculates its output power as

\[ P(k) = K_p(T_{ref}(i - 1) - T_{out}(i - 1)) + K_I I(k) \]  

where

\[ I(k) = I(k - 1) + (T_{ref}(i - 1) - T_{out}(i - 1)) \Delta t \]  

with \( I(1) = 0 \). \( k \) starts at 2 with \( P(1) = 0 \). Note that the index \( i - 1 \) is used in these expressions since we are in the process of calculating \( T_{out}(i) \). If it is not time for a controller update, so \( i \delta t \neq k \Delta t \), then the controller keeps the power level at the previously updated value.

We now discretize the heater dynamics equation.

\[ P(k) + C \rho F(i)T_{in}(i) - C \rho F(i)T_{out}(i) = C \rho V \frac{T_{out}(i) - T_{out}(i - 1)}{\delta t} \]  

In this equation \( P(k) \) is the last updated controller power level. We solve this equation for \( T_{out}(i) \).

\[ \frac{P(k)}{C \rho F(i)} + T_{in}(i) - T_{out}(i) = \frac{V}{F(i) \delta t} (T_{out}(i) - T_{out}(i - 1)) \]  

Rearranging terms gives

\[ T_{out}(i) \left( 1 + \frac{V}{F(i) \delta t} \right) = \frac{V}{F(i) \delta t} T_{out}(i - 1) + T_{in}(i) + \frac{P(k)}{C \rho F(i)} \]  

Finally,

\[ T_{out}(i) = \frac{1}{\left( 1 + \frac{V}{F(i) \delta t} \right)} \left[ \frac{V}{F(i) \delta t} T_{out}(i - 1) + T_{in}(i) + \frac{P(k)}{C \rho F(i)} \right] \]  

A Matlab program was written to implement these equations. Arrays were made for \( T_{in}(i) \) and \( F(i) \) giving the water input temperature and flow for 50 sec. At 10 sec, the reference temperature was changed from 19 °C to 20 °C. At 20 sec, the reference temperature was changed from 20 °C to 20.2 °C. At 30 sec, the water flow was increased
by 10%. At 40 sec, the input water temperature was increased by 0.2 °C. Using the numerical values from the previous subsection, we obtain the output temperature as a function of time given in figure 10. Note that changing the flow at 30 sec and changing the water input temperature at 40 sec did not change the output water temperature except for a brief transient. Also note that the output water temperature followed the reference temperature at 10 sec and 20 sec. The reference temperature was filtered so its value at controller sample \( k \) was the mean of the values over the previous 2 sec. This was done to simulate filtering the local ambient air temperature measurements which will be used as the reference. The filtering accounts for the slow rise time of the output temperature at 10 and 20 sec.

![Tout vs Time](image)

Figure 10: Simulation of output water temperature as a function of time. Details of the steps are given in the text.

The model also gives the controller output power shown in figure 11. The total heater power is given in red, as well as the contribution from the proportional term in blue and the integral term from the controller in green.

The model is very useful for studying the system behavior as the parameters are changed. For instance, if the proportional band is reduced below 0.39 °C, the output water temperature begins to oscillate. Larger proportional bands than 0.43 °C make the system more stable. We believe this behavior results because the controller update time is close to the heater response time. This was tested in the model by lowering \( T_{PB} \) and increasing the heater volume, thus increasing the heater response time. The oscillations stopped. Another important result from the model is that the system oscillates if the measured output temperature is filtered. This causes a delay, which makes the system unstable. This will be discussed further in a later section.
5.6 Air Temperature Sensor

The air temperature measurement for the controller is filtered so that the controller does not try to make the water temperature follow rapid air temperature fluctuations. The thermistor which measures the air temperature is attached to approximately 5 gm of aluminum in the shape of a rectangular block. The thermistor and aluminum are surrounded by a plastic foam insulator. We now estimate the time constant of the filter.

A schematic of the filter is shown in figure 12. The thermistor is shown in red attached to the aluminum in grey. The thermistor temperature is the same as the aluminum temperature. The pink insulation surrounds the thermistor and aluminum.

![Diagram of air temperature filter](image)

Figure 12: Schematic of the air temperature filter.

Consider a one dimensional model of the filter. We assume that the temperature in the insulation changes slowly and is in an approximate steady state. In this case, the heat
The equation in the insulation is
\[ \frac{\partial^2 T}{\partial x^2} = 0 \quad (67) \]

The solution is
\[ T(x) = T_{al} + \frac{T_{air} - T_{al}}{L_{ins}} x \quad (68) \]

where the insulation starts at the aluminum at \( x = 0 \) and goes to \( x = L_{ins} \). \( T_{air} \) is the air temperature and \( T_{al} \) is the aluminum temperature. The heat flux in the insulator is
\[ J = -k \frac{\partial T}{\partial x} = -k \frac{T_{air} - T_{al}}{L_{ins}} \quad (69) \]

where \( k \) is the thermal conductivity of the insulator.

The heat flux causes the aluminum to change temperature.
\[ J_{tot} A = -C \rho V \frac{\partial T_{al}}{\partial t} \quad (70) \]

where \( J_{tot} = 2J \) since heat flows through the insulator on both sides of the aluminum, \( C \) is the specific heat of aluminum, \( \rho \) is the mass density of aluminum, \( A \) is the area of aluminum, and \( V = AL_{al} \) is the volume of aluminum. Combining equations, we have
\[ -2k \frac{T_{air} - T_{al}}{L_{ins}} = -C \rho L_{al} \frac{\partial T_{al}}{\partial t} \quad (71) \]

Simplifying, we have
\[ \frac{\partial T_{al}}{\partial t} + \frac{2k}{C \rho L_{al} L_{ins}} T_{al} = \frac{2k}{C \rho L_{al} L_{ins}} T_{air} \quad (72) \]

Changes in air temperature cause changes in the aluminum (sensor) temperature with time constant
\[ \tau^{-1} = \frac{2k}{C \rho L_{al} L_{ins}} \quad (73) \]

Putting in estimated dimensions and constants from web searches, we have \( L_{al} = 0.005 \) m, \( L_{ins} = 0.010 \) m, \( C = 0.89 \) J/g °C, \( \rho = 2.7 \times 10^6 \) g/m³, and \( k = 0.3 \) W/m °C. We find
\[ \tau \approx 200 \text{ s} \quad (74) \]

This value for the time constant should provide adequate filtering to damp out air temperature fluctuations.
6 Test Plan

The test plan below will work for either an SXR or HXR undulator. If time permits, the tests should be performed on both types of undulators to account for different air cooling of the horizontal or vertical beam pipe, however, the results with water cooling should be very similar. The tests proceed as follows:

1. Demonstrate the need for water cooling.
   (a) Set the undulator gap to 7.2 mm.
   (b) Measure the current and voltage on the corrector wires and set the input power to the beam pipe equal to 3.3 W/m.
   (c) Record the voltages, currents, and sensor temperatures until equilibrium is established.
   (d) Determine the beam pipe and magnet temperature rise.

2. Confirm the water system performance.
   (a) Connect the water chiller and control cart to an undulator beam pipe.
   (b) Measure the water pressure drop at total flow rate of 1.8 gpm.
   (c) Compare to the values calculated in the ANL Engineering Report referenced above.
   (d) Verify that the chiller provides constant temperature water by measuring the water temperature over several hours.

3. Find the sensitivity of magnet temperature to beam pipe temperature.
   (a) Set the undulator gap to 7.2 mm.
   (b) Set the water flow rate to 1.8 gpm.
   (c) Set the chiller temperature to 20 °C. Wait until equilibrium is established.
   (d) Make a step increase in the chiller temperature of 1 °C.
   (e) Monitor the beam pipe temperature and magnet temperature.
   (f) Determine the ratio of magnet temperature change to beam pipe temperature change. Compare to the measurements in step 1.

4. Confirm the heater performance.
   (a) Set the undulator gap to 7.2 mm.
   (b) Set the water flow rate to 1.8 gpm.
   (c) Set the chiller temperature to 19.0 °C.
   (d) Turn on the water heater and its control system.
   (e) Set the heated water temperature to the air temperature.
(f) Start with PID parameters $T_{PB} = 0.43 \, ^\circ\text{C}$, $\Gamma_I = 1 \, \text{sec}$, and $\Gamma_D = 0 \, \text{sec}$. Monitor the water temperature. Look for oscillations. Adjust the PID parameters to achieve the water temperature at the air temperature without oscillations. Record the final PID parameters.

(g) Monitor the heated water temperature and air temperature for approximately one day. Verify that the water temperature follows the air temperature.

5. Find the stability of the system when there are disturbances.

(a) Set a baseline configuration of:
   
   i. Set the undulator gap to 7.2 mm.
   ii. Set the water flow rate to 1.8 gpm.
   iii. Set the chiller temperature to 19.5 $^\circ\text{C}$.
   iv. Set the beam pipe corrector currents to 0 A.

(b) Wait for equilibrium to be established.

(c) Start monitoring all temperatures and currents.

(d) Make a step change in the beam pipe corrector currents of 5 A. This puts an approximate heat load of 12 W on the water cooling system, but the water should carry the heat away with minimal temperature rise. Monitor for one hour.

(e) Make a step change in the water flow to 1.6 gpm. This changes the dynamics of the water cooling system, but the controller should compensate. Monitor for one hour.

(f) Make a step change in the chiller temperature to 19.0 $^\circ\text{C}$. This changes the dynamics of the water cooling system, but the controller should compensate. Monitor for one hour.

(g) Open the undulator gap to 25 mm. Since the beam pipe is at the air temperature, the magnets should not change temperature. Monitor for one hour.

7 Test Results

7.1 Demonstrate The Need For Water Cooling

The purpose of this test is to see what would happen if the high repetition rate beam was sent to the LCLS-II undulators without the water cooling system installed. In this test there was no water in the beam pipe. A current of 5 Amps was turned on in both of the corrector circuits for two days as the beam pipe and undulator temperatures were monitored, and then the current was turned off and the temperature was monitored for two days as the beam pipe and undulator cooled off. The current profile is shown in figure 13. The voltage of the circuits was measured and the resistance of each circuit was calculated. The power into the beam pipe was calculated. The results are shown in figure 14. The blue points show the measured voltage times the measured current. The red line shows the expected power calculated as the measured current squared times the nominal resistance of the wires embedded in the beam pipe. The calculated resistance of the wires in each circuit.
Figure 13: Current vs time in both beam pipe corrector circuits with no water cooling.

is about 0.24 ohms. It is believed that the connectors to the wires each add about 0.01 ohms (based on connector manufacturer data), so the four connectors per circuit add 0.04 ohms. The measured resistance was 0.28 ohms agreeing with the calculated wire resistance plus the connector resistance. If we neglect the power heating the connectors, we believe the power heating the beam pipe is 12 W.

Figure 14: Total power going into the beam pipe corrector circuits.

The temperature changes of the beam pipe, magnets, magnet keepers, and the air are shown in figure 15. The beam pipe temperature rose by about 1.1 °C. The magnet temperatures rose by about 0.7 °C. The keeper temperatures rose by about 0.6 °C. One
can see the effect of the ±0.2 °C air temperature fluctuations in the measurements.

Figure 15: Temperature changes of the beam pipe, magnets, keepers, and air.

If we isolate the beam pipe and magnet temperatures and subtract a fitted line between the ends of the scan, we get the result shown in figure 16. Note the long time constants to come to equilibrium. This is due to the whole undulator being heated by the beam pipe as shown in figure 17. The significant temperature changes to the massive strongbacks and girder show the thermal connections between all parts of the undulator.

We conclude from these results that if water cooling of the beam pipes is not implemented, the magnet temperatures will change by about 0.7 °C at small gap as the high repetition rate beam is turned on. This is far above the 0.1 °C tolerance. As the gap is opened, the magnet heating will be reduced and the air cooling will increase. Some of the effect of the heating is mitigated by measuring the magnet keeper temperature, however, the time constants are long so temperature gradients in the magnets and differences between the magnet temperature and keeper temperature can persist for a long time. Also, the temperatures would have to be continuously monitored and the undulator $K$ values continuously corrected.
Figure 16: Background subtracted temperature changes of the beam pipe and magnets.

Figure 17: Temperature changes of the undulator strongbacks and girder during the test.
7.2 Confirm The Water System Performance

The flow meters and pressure gauges in the water system are manual gauges without electronic readout. The flows and pressures were recorded by hand. The measured flows were

\[ F_{\text{upper\_channel}} = 0.9 \text{ gpm} \] (75)
\[ F_{\text{lower\_channel}} = 0.9 \text{ gpm} \] (76)

The measured pressure drops were

\[ P_{\text{upper\_channel}} = 20 \text{ psi} \] (77)
\[ P_{\text{lower\_channel}} = 22 \text{ psi} \] (78)

These values agree well with the values in the ANL report.

The stability of the water chiller will be demonstrated in the next set of measurements in the test plan.

7.3 Find The Sensitivity Of Magnet Temperature To Beam Pipe Temperature

For this test, the undulator gap was set to 7.2 mm. The chiller was set to 20.2 °C. The heater was off. After approximately one day, the chiller temperature was changed to 21.2 °C in a stepwise fashion. Temperatures were monitored for approximately 3 days. Afterward, the temperature was set back to 20.2 °C.

Figure 18 shows the change in water temperatures and air temperature during the test. The water temperature increased by approximately 0.9 °C. There might be a small calibration error in the chiller, but it does not affect the results of the test.

![Figure 18: Water and air temperatures during the test.](image.png)
Figure 19 shows the change in beam pipe, magnet, and keeper temperatures. The magnet temperatures increase by about 0.6 °C. So the sensitivity of the magnet temperature is

\[
\frac{\Delta T_{\text{mag}}}{\Delta T_{BP}} = 0.7
\]

(79)

This agrees with the results from step 1 of the tests. If we limit the magnet temperature rise to 0.1 °C, the beam pipe temperature can change by at most 0.13 °C.

Figure 19: Change in beam pipe, magnet, and keeper temperatures.

It is interesting how rapidly the magnets and keepers come to equilibrium. In this case, the beam pipe has a constant temperature, while without water cooling, the beam pipe has constant power input. This shows that with water cooling, the keeper temperature fairly accurately gives the magnet temperature.

With the constant temperature beam pipe, the whole undulator heats more rapidly. This is shown in figure 20. The strongbacks and girder come to equilibrium much more quickly than in the test without water and with constant power applied.

### 7.4 Confirm The Heater Performance

For this test, the undulator gap was set to 7.2 mm. The water flow rate was 1.8 gpm. The chiller was set to 19.5 °C. The chiller temperature was set above 19.0 °C because previous measurements showed that the room temperature occasionally went above 21.0 °C. The heated water temperature was set to the air temperature. The PID parameters were initially set to \( T_{PB} = 0.43 \) °C, \( \Gamma_I = 1 \) sec, and \( \Gamma_D = 0 \) sec, but the water temperature had small oscillations. Turning off the integral term resulted in a stable temperature about 0.2 °C below the air temperature. This behavior was expected. The integral term made the water temperature equal to the air temperature, but with small oscillations. The oscillations were made smaller with the following parameters: \( T_{PB} = 0.5 \) °C, \( \Gamma_I = 10 \) sec, and \( \Gamma_D = 5 \) sec. This reduced the proportional gain and the integral term’s gain.
Figure 20: Strongback and girder temperatures during the test.

The derivative term helped minimize controller overshoot. With these parameters, the water temperatures shown in Figure 21 were obtained. The water temperatures (blue, red, yellow, and purple traces) followed the air temperature (green trace). The water temperature still had fluctuations of ±0.1 °C. We will see that these rapid fluctuations do not affect the magnet temperatures.

Figure 21: The heated water followed the air temperature.
7.5 Find The Stability Of The System When There Are Disturbances

For this test, a number of parameters were changed one at a time. The baseline configuration had the undulator gap set to 7.2 mm. The water flow rate was 1.8 gpm. The chiller was set to 19.5 °C. This is instead of setting it to 19.0 °C since the air temperature in this space of the lab occasionally goes above 21.0 °C. The heated water temperature was set to the air temperature. The PID parameters were set to $T_{PB} = 0.5$ °C, $\Gamma_I = 10$ sec, and $\Gamma_D = 5$ sec. The baseline current in the beam pipe correctors was 0 A. The temperatures were monitored with a sampling time of 60 sec.

7.5.1 Change The Power In The Beam Pipe Correctors

Figure 22 shows the magnet temperatures as the beam pipe correctors are powered with 5 A in each circuit putting 12 W into the beam pipe. The yellow and purple traces show the magnet temperatures on either side of the beam pipe. The system is in the baseline configuration up to the left vertical dotted line. At the left dotted line, the power in the beam pipe is increased to 12 W in a stepwise fashion. The power stays at 12 W until the right vertical dotted line. After the right dotted line the system goes back to the baseline configuration. There is no noticeable effect on the magnet temperatures. Note that these sensors use nominal calibrations from the manufacturer and there are offset errors in each sensor accounting for the vertical separation of traces in the plot.

![Beam Pipe, Magnet, and Keeper Temp vs Time, Sen 1](image)

Figure 22: Putting 12 W of power into the beam pipe had no noticeable effect on the magnet temperatures.

7.5.2 Change The Water Flow

Figure 23 shows the effect of changing the water flow. The system is in the baseline configuration up to the left vertical dotted line. At the left vertical dotted 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 dotted line. At the right vertical dotted line, the system goes back to the baseline configuration. The yellow and purple traces show the magnet temperatures. There is no observable effect of the 11% flow reduction. The controller compensates for the reduced flow.

Figure 23: Changing the water flow rate from 1.8 gpm to 1.6 gpm had no noticeable effect on the magnet temperatures.

7.5.3 Change In Chilled Water Temperature

Figure 24 shows the effect of changing the chilled water temperature. The system is in the baseline configuration up to the left vertical dotted line. At the left dotted line the chilled water temperature changes from 19.5 °C to 19.0 °C. The chilled water temperature stays at 19.0 °C until the right dotted line. At the right vertical dotted line, the system goes back to the baseline configuration. The yellow and purple points show the magnet temperatures on either side of the beam pipe. There is no noticeable effect of the chilled water temperature change. The controller compensates for the temperature change.

7.5.4 Open The Undulator Gap

Figure 25 shows the effect of opening the undulator gap. The system is in the baseline configuration up to the left vertical dotted line. Between the two dotted lines, the gap is at 25.0 mm. The system is back in the baseline configuration after the right dotted line. One sees at the 7.2 mm gap that the magnet temperatures have small fluctuations which follow the beam pipe temperature fluctuations. When the gap is opened, the magnet temperature fluctuations go away. There is a very small shift in the temperature of the purple curve, but it is well below 0.1 °C. We conclude that the beam pipe is at the air temperature since the magnet temperatures don’t change when the gap is opened and the magnets are exposed to the air.
Figure 24: Changing the chilled water temperature from 19.5 °C to 19.0 °C produced no noticeable change in the magnet temperatures.

Figure 25: There is only a very small change in the magnet temperatures when the gap is changed from 7.2 mm to 25.0 mm.
8 Future Developments

The technique of locally heating chilled water to ambient temperature described in this note has been shown to work. We have demonstrated that the beam pipe temperature follows the local air temperature. We demonstrated that the magnet temperature doesn’t change when the gap is changed. We have also demonstrated that the magnet temperature is insensitive to fluctuations in the control system parameters and insensitive to the power being applied to the beam pipe. The test system we built meets all the requirements.

Based on the work so far, we also see that there are improvements to the system that can be made. In addition, work is required to make the system ready to be implemented in the tunnel. Some ideas for future developments are:

1. When one looks at the beam pipe water temperature, one sees ±0.1 °C fluctuations. The controller shows fairly rapid power fluctuations on its front panel. A buffer tank should be added to smooth out these fluctuations. After the tests were complete, we did add a buffer tank. It was a cylinder 8 cm in diameter and 25 cm long and is shown in figure 26. The water mixes in the tank for approximately 11 sec. The

Figure 26: A buffer tank was added to reduce the water temperature fluctuations.

buffer tank reduced the fluctuations as shown in figure 27. The fluctuations are now
approximately ±0.05 °C. One might study the fluctuations and reduce them even further.

![Water Temperatures vs Time](image)

Figure 27: A buffer tank helped smooth out the temperature fluctuations.

2. The temperature sensors have small offsets that were seen in the data. Offset calibrations should be done to remove the offsets.

3. The PID parameters should be optimized. The controller has an automatic tuning feature that should be tried. One can also try tuning algorithms that are widely available.

4. The chosen heater only works for water flowing vertically upward in it. This may be a problem for the IHX line where the water comes down from the ceiling. A new heater should be chosen that allows water flow in either a horizontal or downward direction. If the heater has a large enough volume, a buffer tank may be avoided.

5. The chosen heater has the minimum power required in the tunnel. The heater power calculations did not include water temperature and air temperature fluctuations. The heater power rating must be revisited.

6. The system described in this note is stand-alone. The accelerator control system does not need to actively manage it. The accelerator control system should, however, monitor its performance. The signals that go to the accelerator control system must be determined.

7. The system built for this test is a prototype, proof of principle system. A proper engineering design must be made before a system is implemented in the tunnel. Engineering designs can be tested using the equipment and measurement systems in the MMF.
8. The 3.3 W/m heat load on the beam pipe is for the nominal design using the superconducting linac. Under favorable conditions, the heat load might increase to 6 W/m.\textsuperscript{11} The system should be tested under higher heat loads.

9 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 solution is proposed for how to do the water cooling. Water can be brought into the tunnel at the coldest undulator temperature and then the water can be heated locally to the ambient temperature. A system was presented which heated chilled water to the laboratory 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. It appears that this general approach can be successfully engineered to be used in the tunnel.

\textsuperscript{11}H.-D. Nuhn, private communication.