LCLS UNDULATOR HALL TEMPERATURE CONTROL*

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Abstract

The principle function of the LCLS Undulator Hall is to house the undulators which convert electron beam energy into x-ray laser energy via the SASE FEL process. The undulators must be maintained at a very stable and accurate temperature to stay within the tolerances required for FEL operation. Furthermore, even under fault conditions, temperature excursions of the undulators must never go out of a safe operating range, or they will irreversibly go out of tolerance and have to be removed and retuned — a task that could take months. LCLS undulator temperature is mainly determined by the temperature of the surrounding air. In this paper we describe the technical solutions adopted for controlling the air temperature in the Undulator Hall and responding to system faults, and we report on the initial performance.

INTRODUCTION

The LCLS Undulator Hall is a straight tunneled structure, 170 m long, 15 to 30 m underground, containing a string of 33 undulators evenly distributed along the first 130 m of the hall. A high energy electron beam passes through the oscillating magnetic field of the undulators and generates x-ray laser radiation that is used for scientific purposes. The process of generating x-ray laser radiation is highly sensitive to the accuracy of the magnetic fields, as well as to the straightness of the electron beam trajectory at the level of a few microns over 10 m. Permanent magnets in the undulators which generate the magnetic field are sensitive to temperature, as are the mechanical supports of quadrupole magnets that guide the electron beam on its ultra-straight trajectory. The permanent magnets and other components of the undulators do not generate any heat, and they have no direct heating or cooling controls. Their temperature is controlled solely by the temperature of the local environment. We control the environmental temperature by precisely controlling the temperature of the ambient air in the Hall.

DESIGN

The most stringent tolerances for controlling the ambient air temperature are in two categories: (1) maximum allowed temperature range, and (2) temperature stability during operation.

Maximum Allowed Temperature Range

Temperature excursions from the nominal value of $20.0\ C$ can cause irreversible changes to the magnetic field of the undulators [1]. We found that some undulators, which had been stored in insufficiently temperature-controlled areas while awaiting installation, lost field quality and the position of the magnetic axis shifted. The observed changes were dependent on the distance along the undulator (in a way that is not yet fully understood) and were, on average, of order $15 - 25\ \mu$m/C. The axis movement was in the opposite direction if the temperature change was reversed, but with different dependency on distance, so that the original tuning state could not be recovered. In order to keep the effect of these changes within the Undulator error budget, a limit of $\pm 2.5\ C$ was set for the maximum allowable excursion. If an undulator temperature even temporarily goes outside of this range, it would have to be removed from service and retuned - a process that can take a week per undulator.

Temperature Stability During Operation

During normal LCLS operation the ambient temperature along the undulators is required to stay within a range of $20.00 \pm 0.56\ C$ ($\pm 1\ F$) at all times. This temperature tolerance was set based on results from a complex tolerance model for the FEL beam power, which takes into account tradeoffs between different types of tolerances such as betatron orbit mismatch and magnet temperature tolerance. The model predicted an FEL power loss of about 6% due to temperature.

Other Design Criteria

Design criteria were also chosen for average temperature, heat load, cooling effect of the ground and walls, maximum air speed, and maintainability.

The average temperature was chosen to be $20.0\ C$. It is reasonably comfortable throughout the year (though somewhat too cool in the summer) and matches the calibration temperature of the large coordinate measurement machine used to establish the mechanical accuracy of the undulators. The air temperature of the Magnetic Measurement Facility, where the undulator magnets were tuned and measured, was also set at $20.0\ C$ to avoid introducing errors through the imprecisely known temperature coefficient for the response of the undulator strength to temperature change.

A maximum air speed of 3 m/s was used as a design criteria to avoid vibration problems caused by turbulence. Though the average air speed in the actual design is only about 1 m/s, near the supply registers the speed is considerably higher and some care had to be taken to avoid blowing the high speed air directly on the undulator system equipment.

An undulator system budget of 50 W per meter of tunnel length, for the average heat load from undulator equipment was adopted during the design phase of the undulator equipment. In the end, though a good effort was made to keep the equipment heat load at a minimum, the actual heat load was about 66 W/m.

Heating from lighting and other conventional sources was also minimized in the design. Capacity to accom-

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Table 1: Principle heating and cooling loads in the Undulator Hall. Lighting can be either low, high, or off.

	W/m	W
Undulator equipment	60	8500
Lighting (low)	20	3200
Lighting (high)	110	19000
Wall and floor	-24	4100
All others net	7	1200

modate additional heat loads from potential future beamlines and upgrades was provided by including a series of valves in the supply and return chilled water lines that pass through the Undulator Hall. If it becomes necessary, fan cooled units, for example, could be installed where needed without much interruption to LCLS operations.

Design Overview

The design of the air handling and temperature control system features a single 20,000 cfm (570 m^3 per minute) air stream that passes through the entire length of the tunnel from west to east before it is recirculated through two air handler units (AHU) and sent back to the west end through a duct in the Undulator Hall. A schematic is shown in Figure 1. This design was selected over more complex multi-zoned designs because the size, distribution, and stability of the heat loads, allowed it.

Load characteristics

The heat loads in the Undulator Hall are particularly favorable in the sense that they are small, allowing air cooling with small temperature changes and modest speeds; nearly constant in time, and approximately uniformly distributed. The undulator system equipment is left on all the time except during occasional repair. The Undulator Hall is far enough underground that only seasonal temperature changes are seen, and they are greatly damped.

In addition to undulator system equipment heat loads, also present is heat from utility water lines, magnet wiring, AC and DC power cables, and especially lighting. A simplified list of the heat loads is given in Table 1. All water lines that go through the Undulator Hall (hot and cold) were insulated to reduce the heat transfer. Design lighting levels were set for 30 fc (footcandles) for access or installation work and a 5 fc for normal operation. For reference, 5 fc is roughly the nighttime lighting level in a parking garage. In this way a safe low level of lighting could be continuously provided for limited work and operation without causing a thermal transient, while for extended access, office level lighting could also be provided. The cooling effect on the circulating air by the underground walls and floor was estimated to be about -24 W/m and is expected to equilibrate slowly over the next few years [3].

Temperature Protection

To protect the undulator magnets from excess temperature excursions, especially under fault conditions, we implemented a system that shuts down the ventilation fans under certain circumstances [2]. The thermal inertia of the tunnel combined with the low heat load from the equipment provide a thermally safe environment for the undulators while a fault is being corrected. The system has two temperature sensors at the end of the supply air ductwork to monitor the supply air temperature to the Hall. One sensor (Ts1) controls the operation of the heating and cooling control valves. The second temperature sensor (Ts2) provides a reference for air temperature out-of-range shutdown. When the supply air temperature differs by more than ± 1.1 C (2 F) from the set point, an alarm is sent to the monitoring system and technicians are notified. If the air temperature difference continues to increase or decrease to ± 2.2 C (4 F) the Digital Control system will automatically shutdown the operation of the supply and return fans, and air flow in the Hall will cease.

Maintainability

Maintainability with minimal down-time was address by employing two identical AHUs in parallel. When one unit needs service the other can provide half the air flow which is generally enough to keep the temperature within tolerance if the lighting is turned off.

PERFORMANCE

Steady State

Typical performance of the temperature control system can be seen in Figure 2, where the temperature for undulator 17 is plotted during a 24 hour period of normal LCLS operations. The temperature is constant over 24 hours to within ± 0.025 C. The mean temperature is 19.957 ± 0.007; maximum temperature is 19.981; minimum is 19.934. Most of observed variation is due to a small diurnal temperature variation of approximately 0.015 C. This is probably the result of the imperfect regulation of the 10-15% fresh air. The temperature plotted in Figure 2 is the average of three PT100 thermistors that are fixed in the body of the undulator.

Because there is a net heat load in the Undulator Hall, the steady state temperature profile develops a positive gradient along the length of the Hall as the heat is continuously transferred to the air stream. This is shown in Figure 3. The supply air temperature is set to keep the average temperature of the profile to 20.0 C.

Transients

Normally the Undulator Hall is unoccupied because there is a high energy electron beam present during operation. However, during major access periods for maintenance and repairs, the lighting level in the Undulator Hall is brought up to approximately 30 fc and generates an estimated 110 W/m of tunnel heat load. The effect of turning on the high level lighting is to bring the total temperature rise of the air stream to about $2C$, approximately linearly increasing from the supply end to the return end of the tunnels. As a result some of the undulator magnets temporarily go out of operational tolerance but not outside the safe

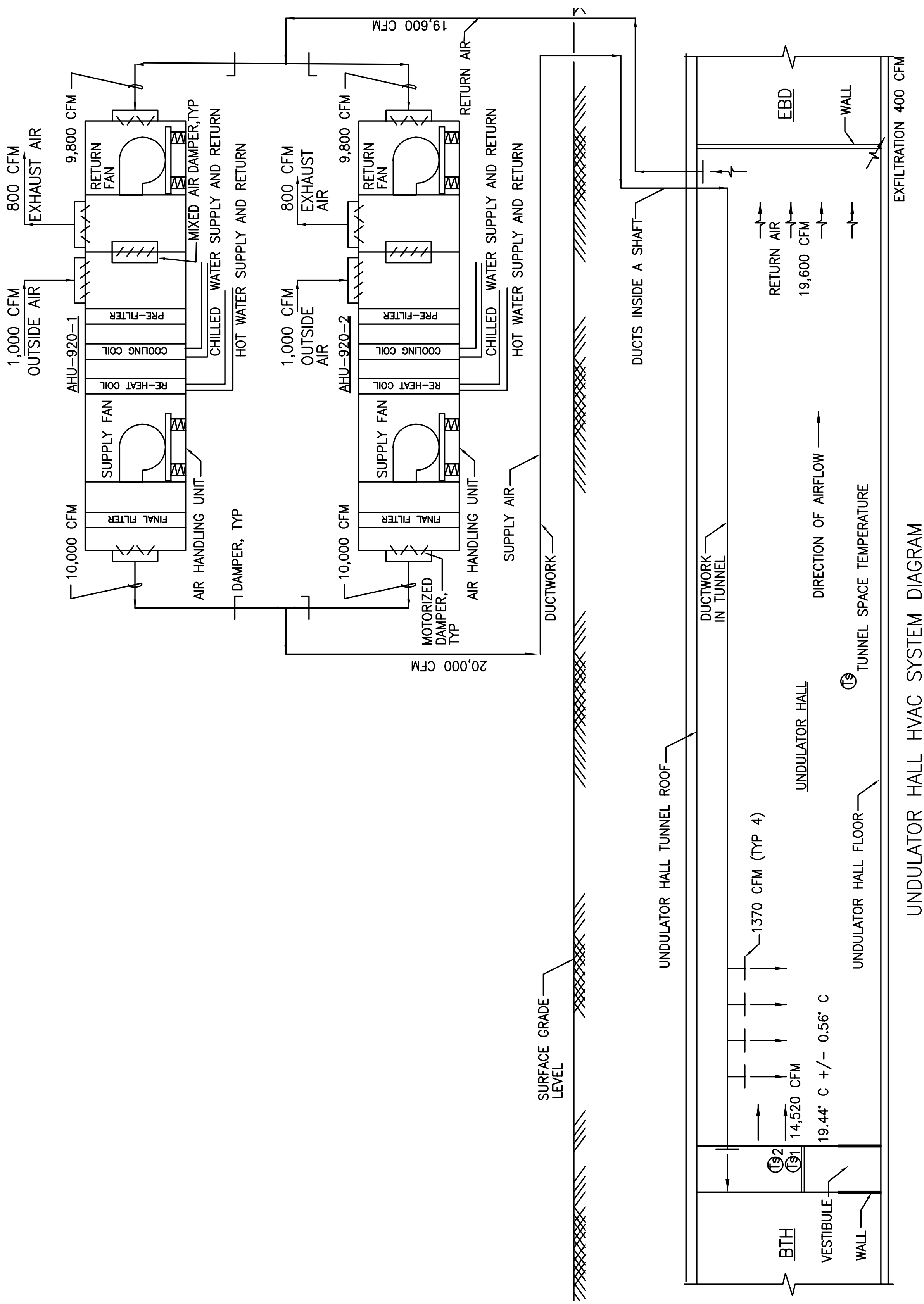

Figure 1: Schematic of the Undulator Hall Air Temperature Control System.

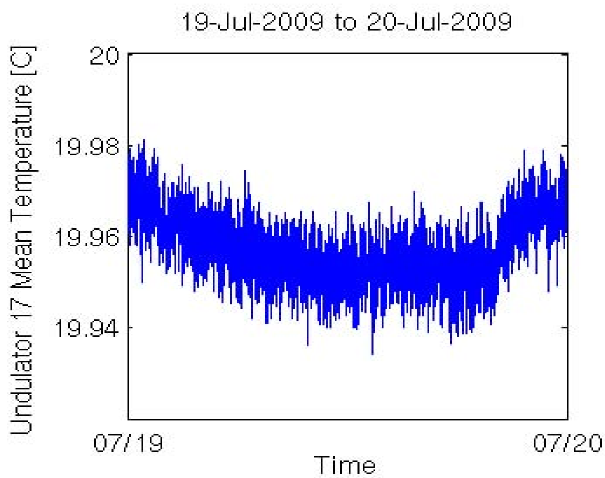

Figure 2: Temperature of undulator segment 17 during normal operation.

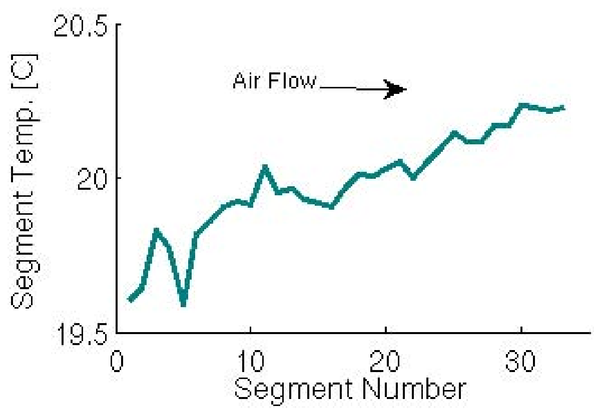

Figure 3: Undulator temperature along the length of the Undulator Hall. The 33 segments of the undulator span the first 130 m of the Hall.

range. Once the lighting is reduced, there is a period of adjustment which is shown in Figure 4. The time constant for the recovery is around 10 hours but it may take several time constants to get back to steady-state behavior, depending on how long the lighting was left on.

Protection System Shutdown

There was one occurrence of the the temperature protection system being activated. The system fans automatically turned off in response to a loss of chilled water to both AHUs, and it stayed off for about one hour. An undulator temperature response is shown in plot in Figure 5. After the fans were turned off the undulator body temperature went up about $0.1\ C$ in one hour. This slow response allowed time to fix the problem with the chilled water without exposing the undulators to a damaging temperature excursion. Once the fans were turned back on the temperature resumed the previous trend. This shutdown event occurred not long after an access when the lighting had been at full level.

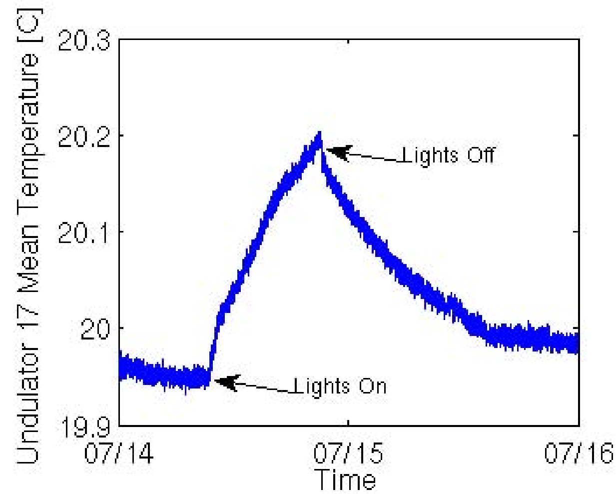

Figure 4: Undulator temperature response to thermal transients caused by turning the lighting on and off.

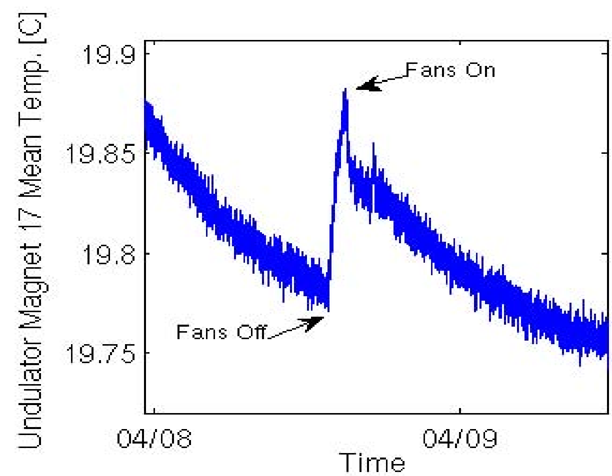

Figure 5: Temperature response of a an undulator to a Protection System automatic shutdown.

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[3] J. Welch, "Air Temperature in the Undulator Hall", SLAC NAL report, LCLS-TN-06-2, (2008), `http://www-ssrl.slac.stanford.edu/lcls/technotes/lcls-tn-02-2.pdf`