LCLS-II 1.3 GHz cryomodule design - lessons learned from testing at Fermilab

J Kaluzny$^1$, J Hurd$^1$, Y Orlov$^1$, Y He$^1$, R Bossert$^1$, C Grimm$^1$, W Schappert$^1$, O Al Atassi$^1$, R Wang$^1$, T Arkan$^1$, J Theilacker$^1$, A Klebaner$^1$, M White$^1$, G Wu$^1$, J Makara$^1$, C Ginsburg$^1$, L Pei$^1$, J Holzbauer$^1$, B Hansen$^1$, R Stanek$^1$, T Peterson$^2$ and E Harms$^1$

$^1$Fermilab, Batavia, IL, 60510, USA
$^2$SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
$^3$email: kaluzny@fnal.gov

Abstract. Fermilab’s 1.3 GHz prototype cryomodule for the Linac Coherent Light Source Upgrade (LCLS-II) has been tested at Fermilab’s Cryomodule Test Facility (CMTF). Aspects of the cryomodule design have been studied and tested. The cooldown circuit was used to quickly cool the cavities through the transition temperature, and a heater on the circuit was used to heat incoming helium for warmup. Due to the 0.5% slope of the cryomodule, the liquid level is not constant along the length of the cryomodule. This slope as well as the pressure profile caused liquid level management to be a challenge. The microphonics levels in the cryomodule were studied and efforts were made to reduce them throughout testing. Some of the design approaches and studies performed on these aspects will be presented. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy. This work was supported, in part, by the LCLS-II Project.

1. Introduction
The design of the LCLS-II cryomodule is based on the TESLA-style cryomodule design[1]. Many of the modifications made to meet the needs of LCLS-II have been validated with the test of the prototype cryomodule. Some changes have been made on cryomodules two and three, and these cryomodules have also been tested. The cooldown circuit was analyzed and comparison to data is shown. Liquid level control and microphonics levels have been a challenge throughout testing.

2. Cooldown circuit
The cooldown circuit in the cryomodule connects the incoming helium flow to the bottom of all of the cavities in the cryomodule. During cooldown, the temperature of the incoming flow is regulated to stay within cooldown constraints. Constraints on all circuits are 10 K per hour cooldown rate and 50 K inlet to outlet temperature difference. The helium gas return pipe also has an additional constraint of 15 K top to bottom temperature difference[2]. Once the cryomodule reaches around 80 K, the constraints are no longer required because most of the thermal contraction has taken place. Figure 1 shows the majority of the cooldown circuit. The circuit consists of a header that has a drop down to each cavity. The drop splits under each cavity and two lines feed into the bottom of each helium vessel. On the end cavities, there are also connections to the liquid level cans not shown in the figure. The circuit is fed by the supply line, line A, through the cooldown valve. After the flow goes through the valve it is routed under the cavity string and through the heater before entering the header.
2.1. Heater

The heater on the cooldown circuit attaches to the exterior of the pipe between the cooldown valve and header. The heater is completely exterior to the pipe, so all heat is transferred through the wall of the stainless steel pipe. The heaters are Minco polyimide thermofoil heaters that measure 25 mm (1 inch) by 307 mm (12.1 inches), and the heat is distributed through copper blocks. The heaters are epoxied to the copper blocks and the copper blocks are epoxied to the pipe. Figure 2 and Figure 3 show the heater assembly, and Figure 4 shows the cross section of the heater assembly. All of the interfaces that require good thermal contact are epoxied with STYCAST 2850FT as part of the final assembly as shown in Figure 5 and Figure 6.

The heat transfer from the wall of the pipe into turbulent flow can be estimated using the Petukhov-
Figure 3. Cooldown circuit heater assembly on the prototype cryomodule.

![Cooldown circuit heater assembly](image)

Figure 4. Cross section of the cooldown circuit heater assembly.

Popov equation modified with the Sieder-Tate term

\[ N_u = \frac{h d}{k} = \frac{(f_F/2) \ Re \ Pr}{1.07 + 12.7(f_F/2)^{1/2}(Pr^{2/3} - 1)} \left( \frac{\mu}{\mu_W} \right)^{0.14} \]  

(1)

and an estimation of the Fanning friction factor for smooth tubes [3].

\[ f_F = (3.64 \log_{10} Re - 3.28)^{-2} \]  

(2)

In the equations above, \( N_u \) is the Nusselt number, \( h \) is the heat transfer coefficient, \( d \) is the pipe inner diameter, \( k \) is the thermal conductivity, \( f_F \) is the Fanning friction factor, \( Re \) is the Reynolds number, \( Pr \)
Table 1. Values of parameters used to compare calculation and experimental data.

| Assumptions          | Calculated Values | Measured Values |
|----------------------|-------------------|-----------------|
| Mass flow            | 0.5 g/s           |                 |
| Pressure             | 1.05 bar          |                 |
| Average bulk temperature | 25 K             |                 |
| Wall temperature     | 80 K              |                 |
| Density              | 2.53 kg/m³        |                 |
| Viscosity at 25 K    | 4.13×10⁻⁶ Pa-s    |                 |
| Viscosity at 80 K    | 8.50×10⁻⁶ Pa-s    |                 |
| Specific heat $C_p$  | 5.23×10³ J/(kg-K) |                 |
| Conductivity         | 3.01×10⁻² W/(m-K) |                 |
| Pipe inner diameter  | 18 mm             |                 |
| Heater length        | 635 mm            |                 |

Reynolds number: $8.56\times10^3$
Prandtl number: 0.718
Fanning friction factor: $8.2\times10^{-3}$
Nusselt number: 25.1
Heat transfer coefficient: 42.0 W/(m²-K)
Heater power: 129 W
Inlet temperature: 5 K
Outlet temperature: 45 K
Average block temperature: 93 K
Heat transfer coefficient: 65.3 W/(m²-K)

is the Prandtl number, $\mu$ is the viscosity of the bulk fluid, and $\mu_W$ is the viscosity of fluid at the wall. Table 1 shows the numbers used to approximate the heat transfer coefficient as well as the heat transfer coefficient based on measured values. The difference in heat transfer coefficients may be due to the flow not being fully developed. There is a 90 degree turn into the first section of the heater and a 180 degree turn into the second section of the heater. These disturbances mix the flow and likely lead to the increased heat transfer.

Figure 5. Epoxy between copper block and heater in cooldown circuit heater assembly.

Figure 6. Epoxy between copper block and pipe in cooldown circuit heater assembly.
2.2. Valve
The valve has a maximum Cv of 1.5 and a 1:1000 equal percentage modified to zero flow profile. With this flow profile, closing the valve 10% cuts the flow approximately in half as shown in Figure 7. This profile accommodates large flow (30-80 g/s) for creating a large temperature gradient when cooling through the transition temperature, and it also accommodates the low flow (0.5 g/s) needed when operating the heater.

The size of the valve was reduced throughout the design process. This reduction led to a less severe failure scenario if all valves in the linac were to open simultaneously, and it also allowed for better control of the flow through the circuit. With a very large valve, the flow is not as limited by the valve, and the resistance of other items in the flow path cause a significant portion of the pressure drop through the circuit. This leads to the mass flow versus valve position deviating from a typical curve as shown in Figure 7.

2.3. Circuit flow
The flow analysis of the cooldown circuit was complicated by the many parallel flow paths. An analysis was done at different temperatures and pressures to ensure that the required flow through the circuit would be available. The results of the analysis are shown in Figure 8. In order to keep the liquid level cans at each end reading the liquid level in the end cavities, a capillary tube is attached from the bottom of the end cavities to the liquid level cans. The wall thickness of these lines was increased to reduce the amount of flow taken during cooldown. It is estimated that around 1/30 of the total flow is taken through these two tubes combined.

3. Liquid level and slope
The tunnel at SLAC has a 0.5% slope, and the test stand was designed to match the 0.5% slope [2]. The cryomodule is around 12 m long, so end to end vertical difference is on the order of 60 mm. An illustration of the slope can be found here [1]. The two phase pipe has an inner diameter of 97.4 mm allowing for a limited range of operation. The alignment of the liquid level cans varies from cryomodule to cryomodule and can further limit the operational range. In the prototype cryomodule, the injection
of the flow into the two phase pipe also caused disturbance in liquid level. A baffle was added on cryomodule two to redirect the flow away from the liquid surface. For cryomodule three and beyond a tee was added in addition to the baffle to further reduce the disturbance due to incoming flow. A more detailed explanation of liquid level management can be found here [4].

4. Microphonics
After the initial cooldown of the prototype cryomodule, observed microphonics (changes in cavity resonant frequency due to external mechanical vibrations) levels were large (up to 15 times the LCLS-II specification) and unstable in amplitude and spectrum. Efforts were made to diagnose and reduce microphonics levels throughout testing of cryomodules. Changes made to cryomodule two including modifications to the cryogenic valves yielded seven of the eight cavities meeting specification. Thermal acoustic oscillations played a role in the large levels of microphonics, and the discovery of sources and mitigation strategies are explained in detail here [5]. The remaining cavity (cavity one) was significantly improved, but it was still around two times specification due to a different mechanical resonant structure. On the prototype cryomodule through cryomodule five, cavity one has a 14 kg gate valve attached rigidly to the end of the cavity. The mass of the gate valve changes the frequency response of the cavity, making it more sensitive to certain mechanical disturbances. Starting with cryomodule six, a bellows has been installed between cavity one and the gate valve. A retrofit is being designed for the cryomodules without a bellows between cavity one and the gate valve.

5. Summary
Three LCLS-II cryomodules have been tested at Fermilab. The prototype cryomodule uncovered some operational issues that have been mitigated in cryomodules two and three. With these tests many of the design features have been validated. The cooldown circuit heater was tested and shown to have a
heat transfer coefficient larger than estimated by calculations. The cooldown valve allowed for high and low flow control through the cooldown circuit. The liquid level control was complicated by the slope, incoming flow, and liquid level can alignment. Microphonics levels were high partially due to thermal acoustic oscillations in the cryomodule and on the test stand. The rigid connection between cavity one and the beamline gate valve led to this cavity still having higher than specification microphonics. A new support for the cavity one gate valve is being designed and is planned to be tested on cryomodule four or five.

References
[1] Peterson, T et al; LCLS-II 1.3 GHz Cryomodule Design - Modified Tesla-Style Cryomodule for CW Operation; THPB119, Proceedings of SRF2015, Whistler, BC, Canada, 2015.
[2] White, M et al; Cryogenic System for the Cryomodule Test Stand at Fermilab; CEC 2015, Tucson, AZ, USA; IOP Conf. Series: Materials Science and Engineering 101 (2015) 012098, 2015.
[3] Albright, L; Albright’s Chemical Engineering Handbook; CRC Press - Taylor & Francis Group, 2008.
[4] Wang, R et al; Operational Experience from LCLS-II Cryomodule Testing; CEC 2017, Madison, WI, USA; submitted to Adv. in Cryo. Eng.
[5] Hansen, B et al; Effects of Thermal Acoustic Oscillations On LCLS-II Cryomodule Testing; CEC 2017, Madison, WI, USA; submitted to Adv. in Cryo. Eng.