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Operational Experience from LCLS-II Cryomodule Testing

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Abstract. This paper describes the initial operational experience gained from testing Linac Coherent Light Source II (LCLS-II) cryomodules at Fermilab's Cryomodule Test Facility (CMTF). Strategies for a controlled slow cooldown to 100 K and a fast cooldown past the niobium superconducting transition temperature of 9.2 K will be described. The test stand for the cryomodules at CMTF is sloped to match gradient in the LCLS-II tunnel at Stanford Linear Accelerator (SLAC) laboratory, which adds an additional challenge to stable liquid level control. Control valve regulation, Superconducting Radio-Frequency (SRF) power compensation, and other methods of stabilizing liquid level and pressure in the cryomodule 2.0 K SRF cavity circuit will be discussed. Several different pumping configurations using cold compressors and warm vacuum pumps have been used on the cryomodule 2.0 K return line and the associated results will be described.

1. Introduction

Fermi National Accelerator Laboratory (Fermilab) is fabricating cryomodules for the Linac Coherent Light Source II (LCLS-II) located at SLAC. LCLS-II is a U.S. Department of Energy project tasked to design and build a world-class x-ray free-electron laser facility for scientific research. LCLS-II is an upgrade to the existing SLAC LCLS X-ray free electron laser, which will be used to observe biological molecular structures, molecular charge distributions, catalytic dynamics, and other processes at the sub-nanometer scale. By utilizing Superconducting Radio Frequency (SRF) cavities in the accelerator instead of normal conducting radio frequency cavities, the X-ray pulse repletion rate is expected to increase from 120 times per second in the LCLS to 1 million pulses per second in the LCLS-II at 4 GeV[1].

LCLS-II Cryomodules are tested on the Cryomodule Test Stand (CMTS) in Fermilab's Cryomodule Test Facility (CMTF) before installation in LCLS-II tunnel. There have been three 1.3 GHz cryomoduless tested at CMTS to date: prototype Cryomodule (pCM), Cryomodule-2 (CM2) and Cryomodule-3 (CM3). This paper focus on the operational experience gained from testing the three cryomoduless including: slow cooldown from 300 K to 100 K, fast cooldown from 50 K to 9.2 K, operation at 2.0 K with static heat load, and operation at 2.0 K with additional SRF and heater power (RF compensation mode). Measured heat loadsto each of the three cryomodule circuits operating at nominal temperature levels of 40 K, 5 K, and 2.0 K are reported. Liquid level control issues encountered during testing and measures taken to address the issue are also discussed.

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2. Cryogenics Infrastructure Overview

An overview of CMTF cryogenic infrastructure supporting CMTS was presented in [1] in 2015. The cryogenic system includes the Superfluid Cryogenic Plant (SCP), the Distribution Box , the Transfer Line and Valve Box ~~between DB and Feed Cap (FC)~~. The cryomodule is connected to the Feed Cap and End Cap . The cryomodule cavitiy circuit is pumped to 2.0 K by Kinney Vacuum Pump. Figure 1 shows a simplified schematic of CMTF cryogenic infrastructure. Because the LCLS-II tunnel in SLAC has a 0.5% slope, CM testing in Fermilab CMTS is also adjusted to 0.5% slope in order to recreate realistic testing conditions.

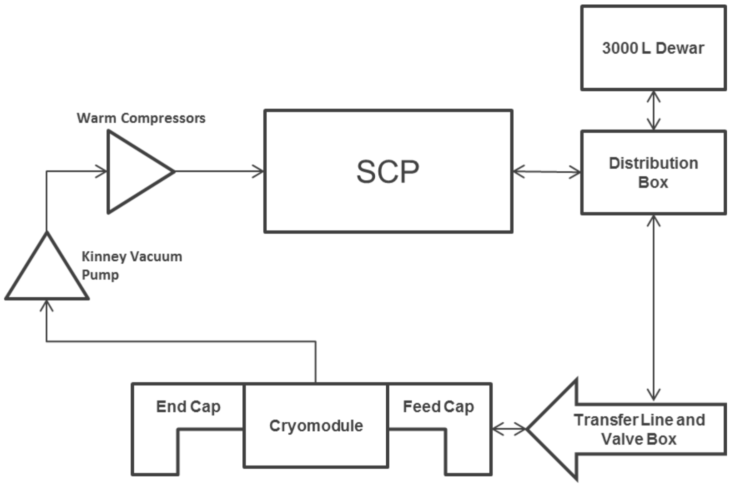

Figure 1. Simplified Schematic of CMTF Cryogenic Infrastructure

3. CM Cooldown/Warmup

3.1. Slow Cooldown/Warmup from 300 K to 80 K

In the supply temperature range of 300 K to 100K the rate at which the cooldown supply temperature to all three cryomodule circuits is dropped is limited to 10 K/hour. Other cooldown/warmup constraints include a maximum radial temperature difference in Helium Gas Return Pipe (HGRP) of less than 15 K, and maximum longitudinal temperature difference in HGRP must be less than 50 K. The cooldown/warmup flow is supplied via the cooldown line into the bottom of the cavity vessel. The cooldown flow rises into the two-phase pipe and HGRP before returning to compressor suction header. Figure 2 is a simplified drawing of single cavity vessel, HGRP, cooldown line and two-phase pipe as installed in the Cryomodule.

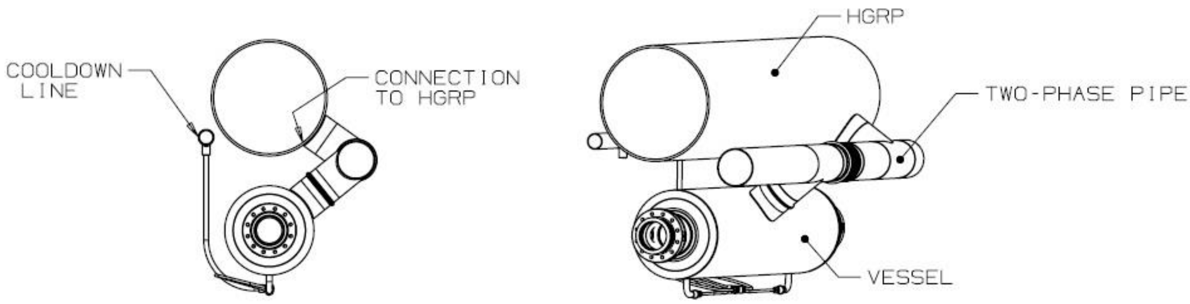

Figure 2. Single Cavity Vessel and Helium Gas Return Pipe (HGRP)

A plot of the temperature during the slow cooldown of CM2 is shown in Figure 3. Throughout the cooldown from 300 K to 80 K, the cooldown flow was supplied from the cooldown/warmup circuit in SCP by mixing 40 K flow with room temperature helium. The temperature of the cooldown supply flow was dropped 10 K every hour if all constraints were met. Mass flow rate into cavity circuit and 40-80 K High Temperature Shield (HTS) were approximately 10 g/s throughout the entire process. The step changes were initially performed by operators to gain experience with the slow cooldown procedure. The slow cooldown procedure takes at least 20 hours, so development of a sequential function controller to control the slow cooldown and reduce operator effort was a high priority. The same procedure and sequential function controller were applied for warmup from 80 K to 300 K, but in the opposite direction.

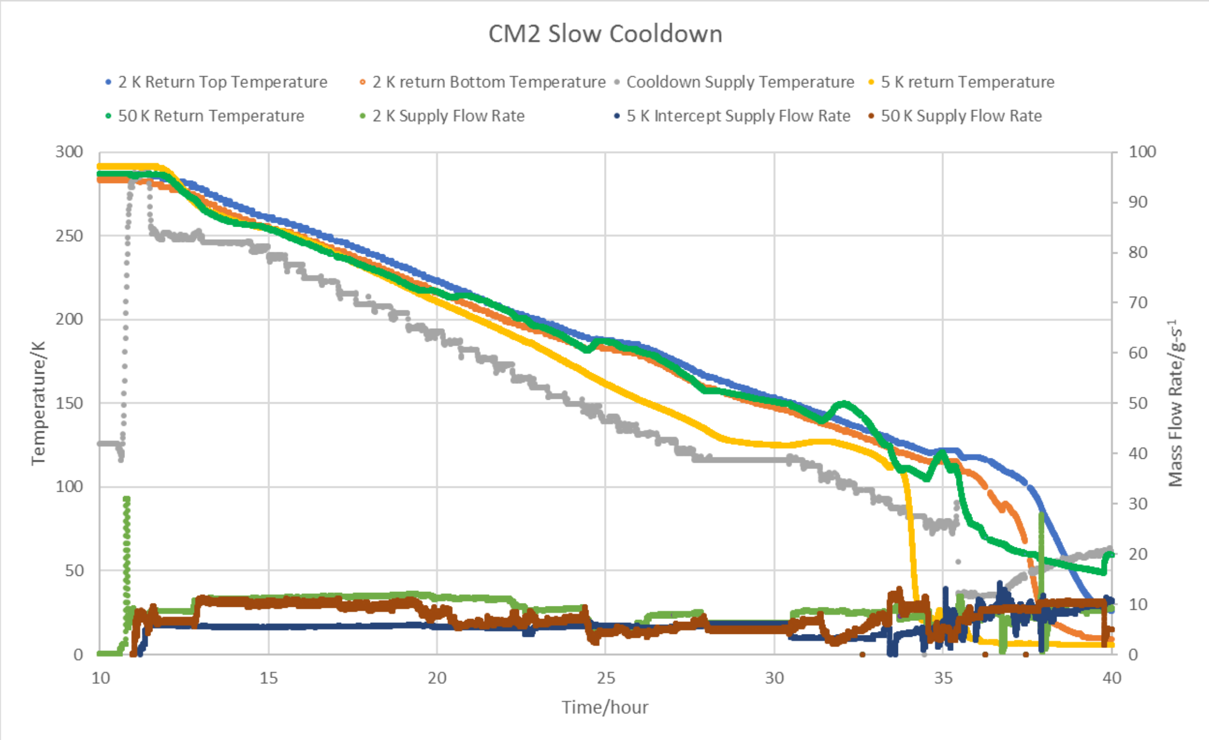

Figure 3. Temperature and Mass Flow Rate during Cooldown

3.2. Fast Cooldown from 300 K to below 9.2 K

The average cryomodule cavity resonance quality-factor Q_0 requirement for LCLS-II is 2.7E10. In order to help achieve this requirement the cavities are cooled down at fast rate through niobium superconducting critical transition temperature (9.2 K) to minimize the remnant magnetic field [2][3]. s The objective is to achieve a large temperature gradient between top and bottom of the cavity to expel maximum remnant magnetic field. The fast cooldown procedure starts with all cavities at approximately 50 K. A minimum of 30 g/s of 5 K helium flow at 3.5 bar are supplied into the bottom of cavities through the cooldown/warmup supply until all cavities are below 9.2 K. CM The cryomodule is then slowly filled with liquid helium before being pumped to 2 K while the refrigerator is rebalanced. Figure 4 shows a typical fast cooldown for pCM, with a cavity supply flow rate of approximately 30 g/s. The cavities are all cooled down from 54-55 K to below 9.2 K. Within an individual cavity, the temperature difference between bottom and top rose quickly to greater than 30 K before decreasing to 0 K. The fast cooldown was completed in less than 10 minutes before all cavities were below critical temperature.

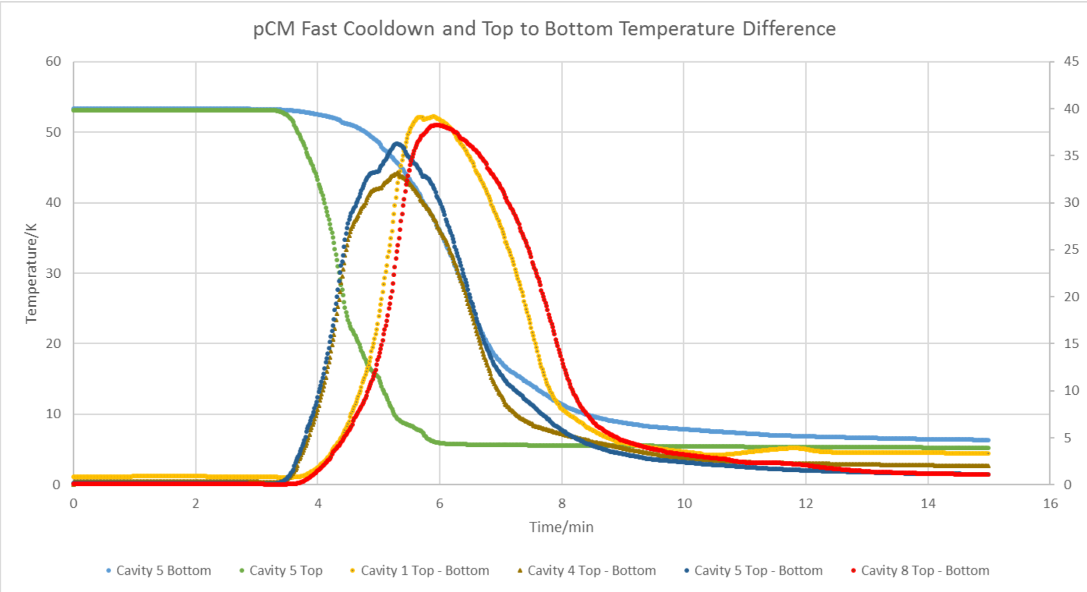

Figure 4. Typical pCM Fast Cooldown and Cavity Top to Bottom Temperature Difference

The maximum liquefaction capacity of SCP is approximately 25 g/s. Therefore, extra steps were taken in order to temporarily boost capacity before the fast cooldown so that the SCP could provide 30-90 g/s of 5 K flow rates for short period of time. These steps include reducing flow into 5 K intercept circuit, turning off heaters internal to the SCP, and adjusting SCP control loop settings to increase the cold end flow rate. There is a temporary build-up in liquid level inventory in the 3000 L dewar just prior to the fast cooldown. During the fast cooldown the 3000L Dewar heater is set at the maximum power of 1000 W. Most supply flow is diverted to the cryomodule cavities during fast cooldown, so liquid inventory starts to boil off from the 3000L Dewar. The extra boil-off from the dewar to maintains the cold end temperature stability.

Figure 5 shows the measured quality factor Q_0 versus fast cooldown flow rate. Compared to slower cooldown at 4 g/s, fast cooldown with 32 g/s or higher improved Q_0 from 2.62E10 to 3.45E10, Flow rate higher than 32 g/s had little effect on Q_0 measurements.

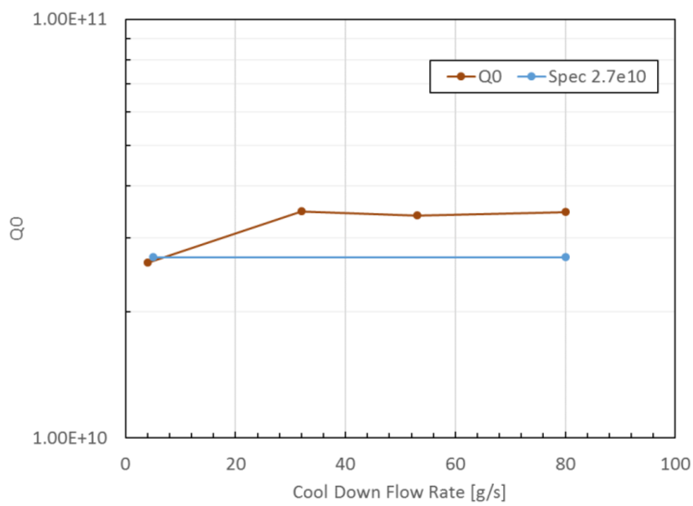

Figure 5. Q0 vs. Fast Cooldown Flow Rate in CM3

4. Cryomodule 2 K Operation

Several issues were discovered after cooldown of pCM. First, the flow rate necessary to maintain liquid level in the2 K circuit is significantly higher than would be expected from the calculated static heat load. As summarized in Table 1, the 2 K circuit flow rate (both supply and return) is approximately 4.7 g/s, which is significantly higher than design estimate. There is also a 1 K temperature increase from the Distribution Box to the Feedcap indicating a large heat load within the distribution system. The liquid level difference between upstream and downstream liquid level can is greater than designed. The cryomodule is seated on a 0.5% slope at CMTS to replicate actual LCLS-II tunnel, so the liquid level is lower in the upstream liquid level can than in the downstream liquid level can as shown in Figure 6. If the alignment is perfect, the difference between two liquid level should be 19.5%. However, as summarized in Table 1the liquid level difference in pCM was 24.2% (3.7% greater than ideal) with no SRF or heater power. Lastly, it was noted that the liquid level difference increased as the dynamic heat load increased, indicating a higher mass flow rate affected the liquid level difference.

Figure 6. Ideal Liquid Level at Upstream and Downstream liquid level measurement cans

4.1. High Heat Load and Remedies

Several sources of high heat load were identified. As shown in Figure 7 ice build-up was found on the pCM JT valve as well as the Distribution Box 2.0 K and 5.0 K circuit instrument lines. The cause of ice build-up was verified to be related to Thermoacoustic Oscillation (TAO) [4]. The JT valve was originally plumbed in reverse direction to minimize potential leak into sub-atmospheric lines, and the thermal intercept on the valve stem wasn't connected to High Temperature Shield. After a shutdown the pCM JT valve thermal intercept was connected and a wiper was added on the valve stem so that there was not continuous gas column between 300 K and 2.0 K.TAOs in the cryogenic distribution system instrumentation lines were mitigated by adding external volume during CM2 and CM3 testing [4].

Figure 7. Ice formation on the cryomodule JT valve and Distribution Box Instrument Line

Data was not available to compare the reduction of heat load before and after thermal intercept was connected because pumping capacity were not sufficient to sustain 2 K (31 mbar) operation before. Therefore, the comparison is before versus after the wiper was installed on the JT valve. The return mass flow rate was reduced from 4.80 g/s to 2.21 g/s, which corresponds to approximately 30 W of reduction in 2 K equivalent heat load.

For CM2 and CM3, the plumbing of JT valve was reversed back to normal flow path with the stem at subatmospheric pressures. Improved TAO mitigation on CM2 and CM3 also led to further reduction of mass flow rate. The 2 K mass flow rate (return flow) decreased from 2.21 g/s for pCM to 1.54 g/s for CM2, and further to 1.08 g/s for CM3.

Two types of flow meters were installed to measure mass flow rate at 2 K level. One Coriolis flow meter with 0-40 g/s range is on 2 K circuit supply within the Valve BoxThe other is a thermal flowmeter with a 0-6 g/s range is on the discharge side of Kinney Vacuum Pump, which measures the return flow rate.

4.2. Liquid Level Control

As mentioned above, the liquid level difference between upstream and downstream liquid level can is greater than expected and increased as the heat load increased. The design operating range for the liquid-vapor interface to stretch the full length of the two-phase pipe is approximately 14% (or ±7%). This correspond to measurement of 64-79% in the upstream can and 83-97% in the downstream can This is limited by the vapor mass flow limit (5 m/s velocity limit) as well as the 2-phase pipe geometry.

Table 1. Liquid Level Difference with Static Heat Load and Dynamic Heat Load

Heat Load	Cryomodule	pCM, before wiper	pCM, after wiper	CM2	CM3
Static Heat Load	baseline liquid level difference, with all supply valves closed	22.5%	22.5%	20.2%	24.1%
	Liquid Level Difference with JT valve regulating	24.2%	22.6%	20.2%	24.2%
	Liquid Level deviation from baseline with JT valve regulating	1.7%	0.1%	0.0%	0.1%
	mass flow rate at 2 K level, supply mass flow meter, in g/s	4.63	2.23	2.02	1.88
	mass flow rate at 2 K level, return mass flow meter, in g/s	4.80	2.21	1.54	1.08
	quality of 2 K flow at JT valve outlet	64.2%	80.8%	75.2%	71.1%
RF compensation mode, with cavity heaters	Heater Power	100 W	80 W	80 W	80 W
	Liquid Level Difference with JT valve regulating	30.1%	26.0%	20.2%	25.4%
	Liquid Level deviation from baseline with JT valve regulating	7.6%	3.5%	0.0%	1.3%
	mass flow rate at 2 K level, supply mass flow meter, in g/s	11.4	8.02	7.8	7.88
	quality of 2 K flow at JT valve outlet	55.1%	57.4%	52.6%	53.4%

A baseline measurement of the liquid level differences in the pCM was made by closing the JT valve, while maintaining CM pressure at 31 mbar in order to determine the liquid level difference with no interference from the vapor exiting the cryomodule JT valve,, This baseline measurent can be used to gauge the effect of misalignment ~~etc..~~ Figure 8 shows the liquid level difference quickly dropped to 22.5% after closure of JT valve. There was also apparent ring-down behaviour when liquid level was balancing out.

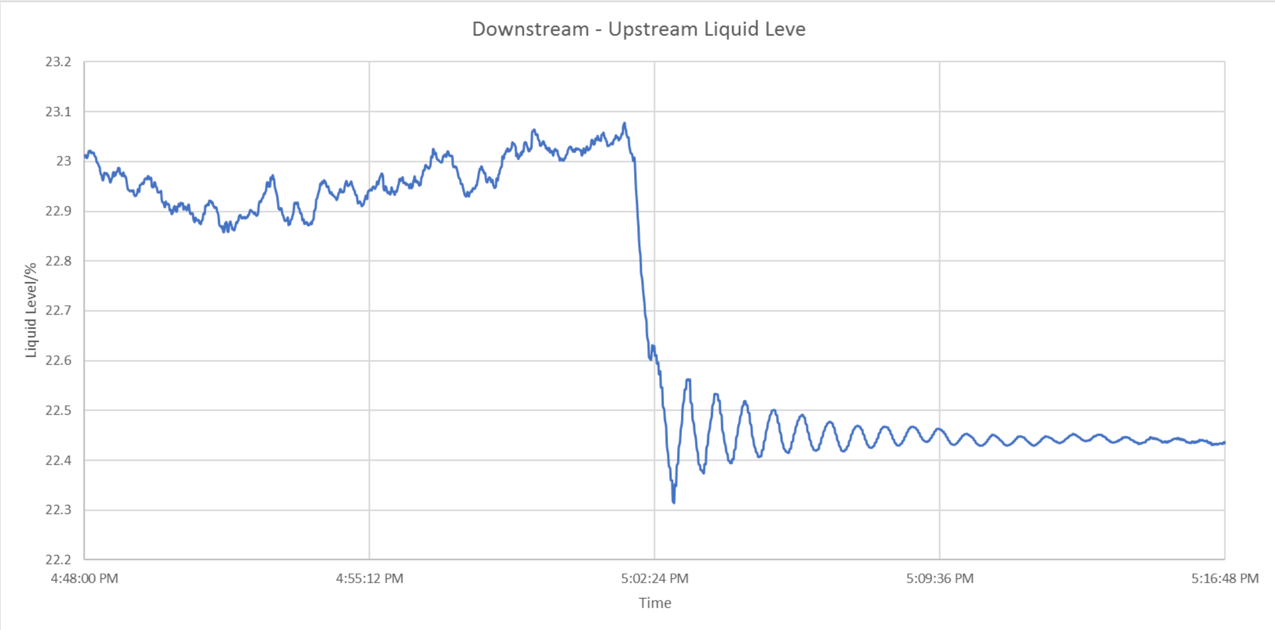

Figure 8. Liquid Level Ring-down after JT Closure

The 2 K supply in cryomodule is injected into the 2-phase pipe between cavities 3 and 4. For pCM, the incoming flow jet was directly blowing on the liquid space, which created a "vapor-dam" or "air-curtain" effect on the liquid level within the 2-phase pipe. The effect is exacerbated as the flow rate increases when the heat load is higher, requiring more flow to maintain constant liquid level. Table 1 shows that when flow rate was increased to compensate for higher heat load, the liquid level difference increased 3-6% compared to the static heat load condition. The flow velocity could be as high as 70% of speed of sound at JT line outlet before flowing into 2-phase pipe.

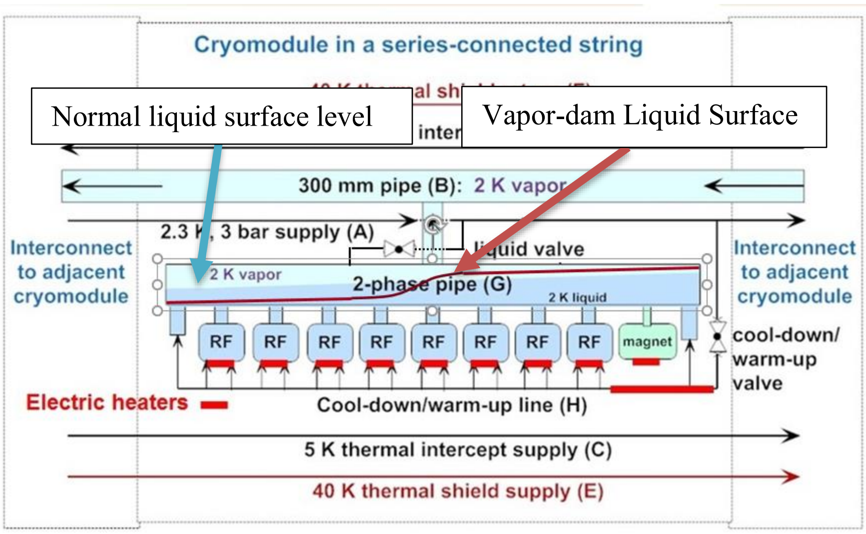

Figure 9. Normal Liquid Surface vs. Vapor-dam Liquid Surface

Figure 9. Normal Liquid Surface vs. Vapor-dam Liquid SurfaceFigure 9 shows the "vapor-dam" effect schematically. The effect likely suppressed the upstream liquid level, creating a higher liquid level difference between the upstream and downstream.

4.3. Modifications from pCM to CM2 and CM3 addressing Liquid Level Issue

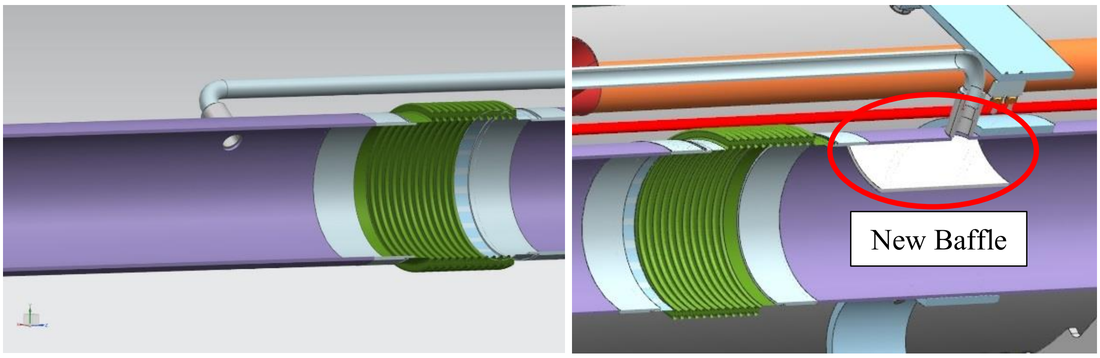

Figure 10. JT Line Connection to 2-phase Pipe - left: pCM left, right: CM2

As shown in Figure 10, a baffle was added within the 2-phase pipe to shield the liquid surface from direct inflow from JT line outlet. When JT valve was regulating at either static heat load or 80 W dynamic heat load, the liquid level difference was essentially the same as the baseline liquid level difference for CM2 (see Table 1).

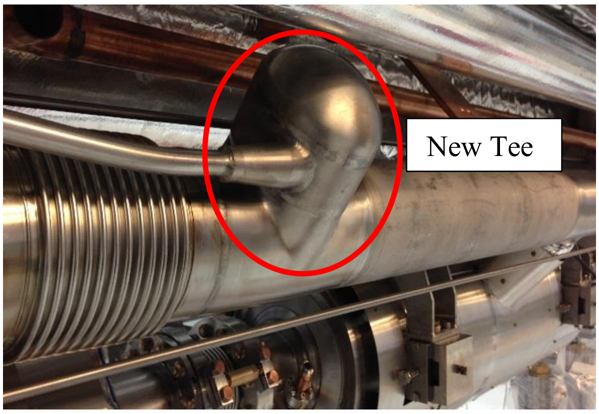

Figure 11. Tee in CM3

In addition to the baffle, a tee was added ~~at~~ between JT line outlet and 2-phase pipe to further reduce flow velocity into the 2-phase pipe (see Figure 11). The liquid level difference increased 1.3% compared to baseline liquid level difference with JT regulating at 80 W dynamic heat load in CM3~~,~~ ~~though~~ the difference at static heat load was still negligible.

Acknowledgments

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