Effects of thermal acoustic oscillations on LCLS-II cryomodule testing

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Abstract. Thermoacoustic Oscillations (TAOs) is a commonly experienced phenomenon in helium cryogenics and in most cases, is an undesirable effect. During LCLS-II prototype Cryomodule (pCM) testing, TAOs were observed in both the Cryogenics Distribution System and in the LCLS-II Cryomodule JT and Cooldown Valves. The TAOs manifested themselves through the usual effect of added heat load to the cryogenic system and ice formation on the oscillating device. However, during cavity testing, the TAOs were also found to significantly contribute to microphonics detuning of the SRF cavities. Systematic studies were carried out and it was discovered that the TAOs could be "turned-off" or substantially decreased by operating at subcritical pressures on the LHe supply. Lastly, various TAO dampening/mitigation techniques were employed to allow operations at supercritical pressure with greatly reduced static heat load and microphonics levels.

1. Introduction

The Linac Coherent Light Source II (LCLS-II) is a U.S. Department of Energy project that will be located at SLAC National Accelerator Laboratory (SLAC) in Menlo Park, CA. The LCLS-II collaboration is tasked to design and build a world-class x-ray free-electron laser facility for scientific research. The LCLS-II accelerator’s design is based on superconducting radio frequency technology, employing thirty-five 1.3 GHz SRF cryomodules and two 3.9 GHz SRF cryomodules in continuous wave operation. Fermilab is charged with building and testing approximately half of the thirty-five, 1.3 GHz Cryomodule (CM) design are two 600 mm length cryogenic valves, one DN6, JT-expansion valve (JT) and one DN10, Cooldown Valve (CD). The prototype cryomodule design had the stem side of the valve seat connected to the supply and thus at positive pressure (3.5 bara operating pressure) and the sealing side of the valve seat connected to the discharge at 23 torr (see figure 1). This configuration is common practice for valves where one side is at negative pressure and the other at positive pressure. Keeping the stem and therefore the helium/air sealing surfaces at positive pressure, avoids the complexity and cost of using cryogenic valves with helium guard gas seals.
Among the many cryomodule functional requirement specifications, the resonance stability requirement is a maximum of 10 Hz peak detuning excursions from 1.3 GHz and a 2K static heat load budget of 9.4 W. At the start of pCM cold testing, initial microphonics were at levels of up to 150 Hz peak detuning and characterized by a very complex and dynamic amplitude spectrum. Figure 2 shows a typical detuning spectrum taken at the start of pCM testing. Spectrum lines are seen to shift rapidly, drift and oscillate in both frequency and amplitude. This dynamic nature of the detuning spectrum suggested the source was likely from the cryogenic system. In addition to high levels of microphonics, the initial 2K static heat load of the CM was measured to be ~42 W, a factor of four higher than the heat leak budget. Lastly, it was noted that the CM valves had ice build-up at the vacuum barrier of the valves. In response to the out-of-spec microphonics levels, a multidisciplinary working group was formed to determine the cause of the high microphonics levels. As presented herein, it was found that nearby TAOs in the JT and CD valves of the CM were the main contributors to the detuning as well as 2K static heat load.

Thermal acoustic oscillations (TAOs) are an oscillatory instability that is often observed in helium cryogenic systems. TAOs can spontaneously occur in tubes when there is a sufficient temperature ratio between the warm and cold ends and where the warm end is closed. The temperature differential drives an acoustic like oscillation, where cold cryogenic fluid rapidly moves up to the warm end of the tube, warms, expands and drives back down to the cold end. It has been shown that the heat load from an oscillating line can be up to 1000 times greater than the thermal conduction of the line [2]. Frequencies of the oscillations typically occur in the 10-100 Hz frequency range. Predicting the existence of TAOs for a given geometry and cryogenic conditions has been the subject of much research, both theoretical and experimental. The early work of Rott and others, established a set of curves or Rott Stability Diagrams [3,4,5,6]. Areas of instability are mapped out with selected dimensionless parameters for various warm to cold length ratios. If the values of the dimensionless parameters for a given system places it within the area of the curve, then oscillations are expected. While the Rott theory has had success predicting TAOs for ideal geometries with near discontinuous temperature distribution, reliably predicting TAOs in real cryogenic systems remains difficult or impractical.

Cryogenic instrumentation lines can provide the ideal conditions for TAOs and as observed during pCM testing, so can the annular space between the stem and bonnet of cryogenic valves. The telltale...
signs of the existence of TAOs in a cryogenic system is a higher than expected heat load, the presence of ice/condensation at the warm end of an oscillating line, and disturbances in the pressure or inline-temperature measurements. TAOs can also induce mechanical vibrations, but this effect normally goes unnoticed in typical cryogenic applications where there is often nearby rotating machinery and other sources of vibrations. However, SRF cavities are particularly sensitive to mechanical vibrations. Mechanical vibrations are compensated by additional RF power, which is limited. If the disturbance exceeds available RF power, gradient regulation is lost, likely causing a trip of the entire accelerator. To give a feel for how sensitive the cavities are to mechanical vibration, the maximum 10 Hz detuning requirement can be equated to ~3 nm of relative longitudinal compression of a 1.3 GHz SRF cavity.

![Detuning Spectrum](image)

**Figure 2.** Detuning spectrum of Cavity 4 taken at the beginning of pCM testing.

2. TAO observations and measurements during pCM testing

It was initially unknown that TAOs in the CM valves was the culprit. Therefore, various cryogenic tests were performed during continuous microphonics data capturing to rule out potential contributions and/or correlations (e.g. flow rates were varied, entire cryogenic circuits were isolated, etc). During these tests, it was discovered that the microphonics levels could be reduced to a level close to specification, by dropping the supply pressure below the critical point (~18 psig). Furthermore, the reduction in microphonics was nearly discontinuous when going between super and subcritical pressure, as seen in figure 3. In conjunction with the drop in microphonics, the ice at the warm end of the JT valve melted away, the steady state flow rate reduced from 4.7 g/s to 1.75 g/s and the supply pressure stabilized. This coincident combination of improvements gave strong supporting evidence that the main source of high microphonics and 2K heat load was TAOs in the annular space of the JT and CD valves and that the TAOs collapse at subcritical pressures.
The precise reason why TAOs are not sustained in the valve’s annular space at subcritical pressures is not fully understood. It may be related to the phase separation that occurs at subcritical pressures. The mass density from 5K supercritical fluid (128 kg/m³) to that of saturated vapor (39 kg/m³) drops by a factor of approximately three. Since CMTS does not have a J-T heat exchanger to recover refrigeration from the CM 2K boil-off, the supply temperatures are high (> 5K) and as a result the vapor fraction is high. During the super to subcritical transition, the stem discontinuously goes from being filled with a high density quasi-liquid at supercritical temperatures to a low-density vapor that can no longer support the TAO. It is unknown if the TAOs in the valves would be supported at subcritical temperatures with high liquid fraction.

Continuous operation at subcritical pressures is not practical due to cryogenic system instability issues that arise from forced two-phase flow. Therefore, the TAOs needed to be mitigated by other means to allow normal operation at supercritical pressures. In addition to TAOs in the valves, there were known sources of TAOs in various instrumentation lines in the Distribution Box located ~50 m away from the CM. Figure 6 shows the noisy pressure measurements by transducers on oscillating instrumentation lines. The pressure fluctuations are as much as +/- 1.5 psig from nominal.

3. TAO mitigation techniques employed
After establishing the dominate source of microphonics as TAOs, various mitigation techniques were applied to the CM valves, suspect CDS valves and CDS instrumentation lines.

3.1. Valve TAO Mitigation
For the valves, two techniques were used:

1. CM JT and CD valves were replumbed such that the annular space was at negative pressure and the sealing surface at positive pressure.

2. Wiper rings or convection brakes were added along the valve stem to dampen the oscillations.

Figure 3. (a) Peak detuning measured during supercritical to subcritical transitions. (b) Photographs of valve body with supply at supercritical pressure and (c) at subcritical pressure.
The first technique was substantiated by the fact that the TAOs were eliminated when operating the supply at subcritical pressures. Recall from figure 1 that the original pCM design had the stem plumbed such that the annular space between the stem and bonnet is at the supply pressure. By reversing the valve, the TAOs are eliminated because the valve’s annular space would be at the subatmospheric pressure of the CM (23 torr) and therefore much less than the critical pressure of 18 psig. To verify this hypothesis before making a design change, the pCM supply pressure was throttled using a CDS valve upstream of the JT valve to the point that the JT valve stem was at 23 torr. The result was the disappearance of the valve ice, reduction in static heat load and microphonics levels were improved even further than seen at positive subcritical pressures (e.g. 8-12 psig). This technique of reversing flow could not be applied to CDS valves since they see the same supercritical pressure on both sides of the valve. Only valves that throttle to subatmospheric or subcritical pressure can potentially benefit from a reversal.

The purpose of the second technique is to disrupt or dampen the TAOs by installing a ring of material, called a wiper or convection break around the valve stem to fill-in the annular space. The Rott stability theory predicts TAOs cannot exist with warm/cold temperature ratio of about six and was verified experimentally [3,6]. To be conservative, valve wipers were added at predicted temperature locations such that the temperature ratio between two wiper locations was no more than 2-3 and with a concentration of wipers at the cold end. Figure 4a shows an example of a temperature profile calculated based on axial and radial conduction through the valve stem, helium filled annular space and valve bonnet. The knee in the profile is due to a 50 K thermal intercept. Figure 4b shows a DN10 valve with installed wipers and corresponding theoretical temperature locations. Since these valves will be in high radiation environments the wiper material used was PEEK (Polyetheretherketone). Figure 4c shows close-up photo of a valve wiper. The wiper is a split ring that snaps around the valve stem and is trapped in place by stainless steel (SS) banding material tack welded onto the stem. The multiple wiper technique was applied to both the CM valves and many of the CDS valves.

Figure 4. (a) Calculated temperature profile of DN10 valve. (b) Approximate wiper locations with corresponding temperature (c) Wiper details
A single wiper near the cold end was tested on the pCM. The 2K static heat load was greatly reduced to 11 W. However, the microphonics levels at supercritical pressure only modestly improved, remaining well above spec. Figure 5 shows a plot of a supercritical to subcritical transition done with single wipers installed. For this test, a temperature sensor was attached to the top of the valve bodies to give indication of any TAO activity in the valve. The plot shows that at supercritical pressures, the JT and CD valve body temperatures were 2-10°C colder than room temperature, but warmer than water freezing temperature. After transitioning to subcritical pressure, the valve bodies warmed-up to room temperature. Most TAO activity was dampened with a single wiper, but some activity exists and thought to be confined above the wiper because the static heat load was so low.

3.2. Instrumentation line TAO Mitigation

It is well documented that TAOs can be greatly reduced, if not eliminated, by adding a second oscillator connected externally to the existing oscillating line [2,7]. If the second system is designed properly and has the same impedance as the acoustic wave in the half-opened tube, the incoming wave will be completely absorbed [7]. Predicting the precise volume and orifice size of the dampener can be unreliable. Instead, it is more practical to create a variable dampener by utilizing a variable orifice (i.e. micrometer valve). A picture of the dampener assembly is shown in figure 7a. We used 300-1000 ml sample volumes and a Swagelok metering valve. A high-speed pressure transducer (102A10 PCB Piezotronics) was also incorporated upstream of the metering valve to measurer the TAOs. Tuning the dampener was done by measuring the PT using an oscilloscope while adjusting the metering valve until the oscillations were dampened. In some cases, volume sizes were changed. Figure 7b shows an example oscilloscope capture during the micrometer valve adjustment. This technique was used on all known instrumentation lines with TAOs. Figure 6 shows pressure measurements of these lines before and after dampeners were added. One of the dampened instrumentation lines was part of the cavity supply circuit upstream of the CM. Figure 7c shows the effect of dampening this line on cavity supply temperature. With the TAO dampened the supply temperature drops from ~5.5K to 4.75K, resulting in better quality helium and therefore lower steady-state flow rates.
Figure 6. Pressure fluctuations measured in CDS instrumentation lines with TAOs (a) before adding dampeners (b) with dampeners.

Figure 7. (a) Typical dampening assembly used; (b) oscilloscope data capture during valve adjustment; (c) Plot of cavity supply temperature and pressure measured with and without TAOs dampened on the corresponding instrumentation line.
4. Final results
Table 1 summarizes the steady state flow rates and pk RMS detuning seen at various stages of CM testing. After implementing all the TAO mitigations, the static heat load was reduced from 42 W to 11 W with corresponding mass flow rates of 4.6 g/s and 1.54 g/s. Note that with a single wiper on the JT and CD valves only, the static heat load was already reduced to 11 W. The addition of the TAO dampening volumes and multiple wipers to the CDS valves helped reduce the static heat load of the supply, thus reducing the steady-state mass flow from 2.21 to 1.54 g/s. The average peak detuning was reduced by an order of magnitude, with all eight cavities at or below specification, except for cavity 1. A final test was completed to determine if either the multiple wipers or the valve reversal was the dominate improvement. Two measurements were made, one using valve stems without wipers but reversed (stem at negative pressure) and another done with a non-reversed (stem at positive pressure) valve but with multiple wipers installed. Both tests yielded the same approximate average peak detuning of 11 Hz and static heat load of 11 W, meaning both methods successfully eliminated the TAOs in the valves.

| TAO Mitigations          | Supply Pressure [psig] | Supply Temp [K] | S.S. Flow Rate [g/s] | Static Heat Load [W] | Ave Pk Detuning [Hz] |
|--------------------------|------------------------|-----------------|----------------------|----------------------|----------------------|
| None                     | 35 (super)             | 5.24            | 4.7                  | 42                   | 102                  |
| None                     | 13 (sub)               | 5.00            | 1.75                 | x                    | 11                   |
| Single valve wipers      | 35 (super)             | 5.61            | 2.21                 | 11                   | 55                   |
| Multiple valve wipers    | 35 (super)             | 5.44            | 1.54                 | 11                   | 11                   |

1Average pk detuning from all 8 cavities taken from a 7 hr capture at 1 kHz

References
[1] White M et. al. 2014 “Cryogenic System for the Cryomodule Test Facility at Fermilab”, AIP Conf. Proc. vol. 1573, 179-186
[2] Ditmars D and Furukawa G 1965 “Detection and Dampening of Thermal-Acoustic Oscillations in Low-Temperature Measurements” Journal of Research of the National Bureau of Standards—C. Engineering and Instrumentation, vol. 69C, No. 1
[3] Rott N 1973 “Thermally Driven Acoustic Oscillations. Part II: Stability Limit for Helium” Journal of Applied Mathematics and Physics, vol. 24
[4] Gary J 1988 “A Numerical Method for Acoustic Oscillations in Tubes”, International Journal for Numerical Methods in Fluids, vol. 8, 81-90
[5] Yazaki T, Tominaga A and Narahara Y, 1979 “Stability limit for thermally driven acoustic oscillation” Cryogenics, 393-396
[6] von Hoffman T, Lienert U and Quack H, 1973 “Experiments on thermally driven gas oscillations”, Cryogenics, 490-492
[7] Luck H and Trepp C, 1992 “Thermoacoustic oscillations in cryogenics. Part 3 avoiding and damping of oscillations”, Cryogenics, vol. 32, No. 8

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