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PASSIVE MICROPHONICS MITIGATION DURING LCLS-II CRYOMODULE TESTING AT FERMILAB*

J. P. Holzbauer†, B. Chase, J. Einstein-Curtis, B. Hansen, E. Harms, J. Kaluzny, A. Klebaner, M. McGee, Yu. Orlov, Yu. Pischalnikov, W. Schappert, R. Stanek, J. Theilacker, G. Wu, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
T. Peterson, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

The LCLS-II project calls for cryomodule production and testing at both Fermilab and JLab. Due to low beam loading and high cavity quality factor, the designed peak detuning specification is 10 Hz. Initial testing showed peak detuning up to 150 Hz with a complex and varying time-structure, showing both fast (1-2 second) and slow (1-2 hour) drifts in amplitude and spectrum. Extensive warm and cold testing showed thermoacoustic oscillations in the cryogenic valves were the primary source of the microphonics. This was mitigated by valve wipers and valve re-plumbing, resulting in a greatly improved cavity detuning environment. Additional modifications were made to the cavity mechanical supports and FNAL test stand to improve detuning performance. These modifications and testing results will be presented.

INTRODUCTION

The LCLS-II Project is a Department of Energy funded hard X-ray laser to be installed and operated at SLAC National Accelerator Laboratory. This machine is designed around a superconducting linear accelerator (linac), allowing much greater beam power and thus higher X-ray brightness. Cryomodule fabrication and testing is done at partner laboratories in the US, 18 cryomodules from Jefferson Lab and 17 from Fermilab. These test stands have the ability to cool the cryomodule components down to the designed 2K operating temperature, and test their performance before they are shipped to SLAC. While these tests have, in general, shown great results [1], the detuning was initially measured well outside specification.

Superconducting RF systems are particularly sensitive to vibrational disturbances, due to their very narrow RF bandwidths. These disturbances can come from many sources, including large externally driven motion, weakly-driven internal mechanical resonances, and vibration from cryogenic sources. LCLS-II uses TESLA-style cavities and a cryomodule design similar to the ones used for the European XFEL, modified for greater Higher Order Mode power and higher cryogenic losses among other changes. With a longitudinal sensitivity of 300 kHz/mm, only 20 nm of motion is required to reach the specified peak frequency deviation from 1.3 GHz of 10 Hz.

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†jeremiah@fnal.gov

FERMILAB CMTS-1

At Fermilab, assembled LCLS-II cryomodules are tested in the Cryomodule Test Stand [2]. Each cryomodule is mounted and aligned between two fixed end caps which provide all cryogenics and vacuum connections and mimic the tilt of the LCLS-II tunnel at SLAC due to its 0.5% slope.

The test stand features a dedicated cryoplant to supply cavity and shield helium flows, LLRF/HPRF controls and amplifiers to drive each cavity individually, and instrumentation and controls for cryomodule testing, including all production sensors and additional diagnostics. All of these signals are logged in the Fermilab controls system, ACNET. Most notably, the LLRF control system includes the functionality to capture RF signals, including calculated detuning, for all eight cavities simultaneously and synchronously at 10 kHz for an arbitrary amount of time. This capability proved to be a very powerful diagnostic tool.

PROTOTYPE CRYOMODULE TESTING

F1.3-01 (the first cryomodule produced at Fermilab) was installed in CMTF in August 2016 [2]. During initial testing, it was discovered that the detuning environment was significantly worse than expected, up to 150 Hz peak detuning. The amplitude and spectrum of the detuning was also found to be highly variable on several different time constant, from seconds to hours (Figure 1). This indicated a significant and complex issue that would require serious effort to diagnose and mitigate. A microphonics working group was formed, including experts in LLRF, cryomodule test experts, mechanical engineers, cryogenic engineers, resonance control, and LCLS-II project management to guide testing and mitigation.

Initial efforts at diagnosis and mitigation focused on warm measurements of ground motion and vibration sources while the cryomodule was warmed after initial testing, although nothing was found to match the detuning patterns seen during cold testing. During cold testing, correlation studies of these lines with cryogenic parameters (temperatures, pressure, valve positions, etc.) were unsuccessful.

The major conclusion from this data was that the detuning was not broadband white noise exciting mechanical resonances in the cryomodule. This strongly indicated that the source was a narrow-band, cryogenics-dominated acoustic process.

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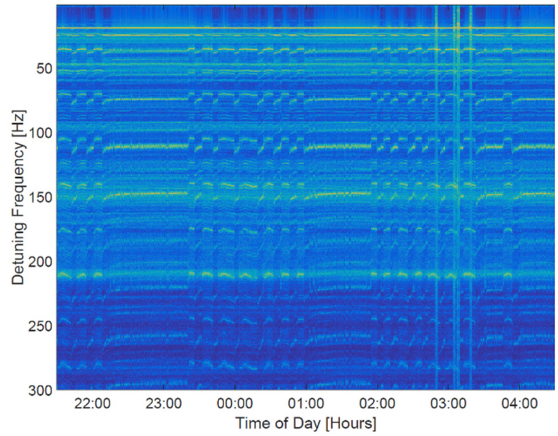

Figure 1: Spectrogram of the captured detuning of cavity 1 on the FNAL pCM (F1.3-01), 2017/01/10. 7 hours of continuous capture at 2 MV/m in SEL mode. Cryogenics in default configuration.

The cryogenic distribution system parameters were varied and tested in different configurations to attempt to diagnose the source of the disturbance, including valve position, flow modulation, and changing supply flow pathing. These tests either showed either no change or inconclusive change in the cryomodule detuning environment.

During testing, the helium supply pressure was unintentionally dropped from the nominal 36 psig to 15 psig, below the super-critical transition pressure for 5K helium. This was briefly correlated with a significant drop in microphonics for a few minutes until the supply pressure recovered. The strong correlation between peak microphonics and the criticality transition was demonstrated later, as seen in Figure 2.

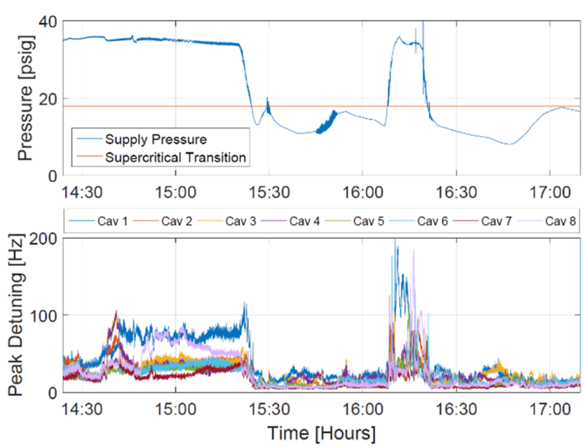

Figure 2: Supply helium criticality transition. Top plot is helium supply pressure, bottom plot is cavity peak detuning.

This transition is correlated with many of the main detuning lines winding down in frequency (like the square root of supply pressure) and turning off around transition.

While this mode is certainly not a viable operational mode, it became a very instructive mode for diagnosis.

THERMOACOUSTIC OSCILLATIONS

The majority of the detuning was traced to the cryogenic supply valves on the cryomodule, added to the module design in a change from the XFEL design for the fast cooldown requirements and linac slope. These valves had been plumbed such that the gas column was common with the supply pressure. These valves were experiencing thermoacoustic oscillations (TAOs), a temperature/pressure instability that drives cold gas up and down in the valve column driven by a temperature difference. Normally, these are a concern because they drive significant cryogenic heat loads, but in this case they were also found to cause significant cavity detuning. Additional signs of TAOs included icing on the valve bonnets and a significant reduction in required supply flow in the subcritical configuration.

In order to mitigate this problem, the valve was reconfigured and valve stem wipers were added. First, the valve flow was reversed such that the valve stem is at the cavity pressure instead of supply pressure, significantly reducing the mass available for the oscillation. Second, the valve stems were modified to include valve stem wipers, small rings of PEEK (for radiation hardness) to interrupt the annular region of the valve stem, acting as damping terms in the oscillation. The location of these rings was optimized [3] to keep the temperature ratio of any given segment to less than 4 (Figure 3).

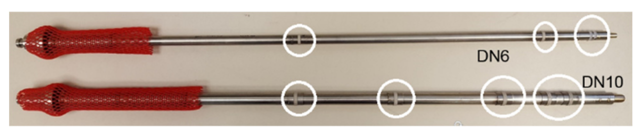

Figure 3: Optimized valve stems with wipers added (circled in white.

These changes were made and first tested on F1.3-02. Measured detuning showed a significant improvement over previous testing, with both lower overall amplitude and far more stable spectral content, as seen in Figure 4.

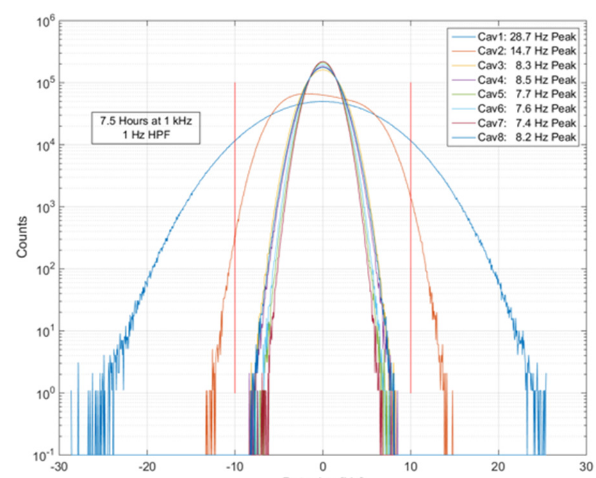

Figure 4: F1.3-02 detuning histogram. 7.5 hours of continuous data measured at low field in SEL. Includes TAO improvements including flow direction and stem wipers on all valves. LCLS-II specification is plotted as vertical red lines.

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CAVITY 1 MECHANICAL SUPPORT

The cavity in position 1 (upstream end of the cryomodule) always exhibited higher detuning than the others in all configurations. As seen in Figure 4, most cavities saw significant improvement with the TAO modifications, but cavity 1 remained roughly a factor of two above the rest. This was diagnosed as a mechanical connection issue and corrected with a cavity string change implemented in large modules. The details of this are presented elsewhere at this conference [4].

OTHER ASSEMBLY CHANGES

Other, minor modifications were made to the cryomodule assembly, generally driven by best practices developed in previous SRF machines. These changes included identifying and securing potential loose components in the cold string to prevent resonances.

CRYOGENIC VALVE LEAKAGE

During the testing of F1.3-04 and F1.3-07, sudden large microphonics was observed on the upstream cavities 1-4. These cavities are also notably elevated due to the cryomodule's tilt. Eventually it was discovered that the second cryogenic valve on the module, the cooldown valve, was stuck/blocked and was leaking significant mass flow even though it was supposed to be closed. This caused significant flow through the cooldown circuit in the module, leading to bubbling preferentially through the upstream cavities. This was unusual because this sort of bubbling was generally thought to be characterized by white or broadband disturbances, but the very low viscosity of superfluid helium led to narrowband detuning.

Attempting to remove the blockage with valve cycling, increased preload, and actuator recalibration were unsuccessful, so the cryomodule was warmed to 30 K and the valve stem was swapped with another. This cleared the blockage, and with the valve seated properly again, the cooldown circuit temperature returned to normal (20-30 K during testing) and the additional microphonics disappeared. The exact cause of the blockage is unknown, but contamination is suspected. The reversed valve plumbing requires gas guard valves to prevent long-term contamination, but it is suspected that the repeated connection/disconnection process of cryomodule testing was the source of the contamination.

ACTIVE RESONANCE CONTROL

Early in the process, additional effort was added to the project baseline to include active resonance control into the test stand operation. This is to use the fast piezoelectric tuners on each cavity. Techniques were developed to both compensate for slow (< 1 Hz) drifts and suppress low frequency detuning (< 150 Hz). This work and results are presented elsewhere at this conference [5].

HELIUM INJECTION MODIFICATIONS

Initial testing showed significant correlation between liquid levels and input flow rate. This was identified as weiring due to significant flash gas fraction in the injection flow. Closing the JT valve caused the differential liquid level to oscillate with a 45 second period that represents sloshing of the helium in the 2-phase pipe, seen in Figure 5.

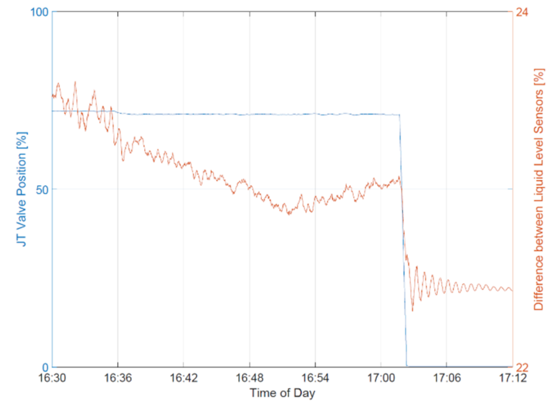

Figure 5: Change and oscillation in differential liquid level after helium flow was stopped.

Initially, the helium inlet flow was injected directly onto the 2-phase pipe liquid surface. TAO mitigation improved the flash gas fraction, and a baffle was installed below the injection point to protect the liquid surface. In addition, the injection was modified to be tangential into a volume added to the 2-phase pipe. This allowed the injection flow to slow and start phase separation, reducing the weiring and flow-dependant noise.

CONCLUSION

LCLS-II cryomodule production and testing is underway at Fermilab and JLab. Initial testing showed microphonics well above specification. Many changes including TAO mitigation in injection redesign improved detuning performance to near or within specification.

ACKNOWLEDGMENTS

This paper represents the work of many people of many disciplines over many months of testing and design effort both at Fermilab and at partner laboratories as well as collaborators throughout the SRF world.

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