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MICROPHONICS IN THE LCLS-II SUPERCONDUCTING LINAC*

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Abstract

The LCLS-II project has installed a new superconducting linac at SLAC that consists of 35 1.3 GHz cryomodules and 2 3.9 GHz cryomodules. The linac will provide a 4 GeV electron beam for generating soft and hard X-ray pulses. Cavity detuning induced by microphonics was a significant design challenge for the LCLS-II cryomodules. Cryomodules were produced that were within the detuning specification (10 Hz for 1.3 GHz cryomodules) on test stands. Here we present first measurements of the microphonics in the installed LCLS-II superconducting linac. Overall, the microphonics in the linac are manageable with 94% of cavities coming within the detune specification. Only two cavities are gradient limited due to microphonics. We identify a leaking cool down valve as the source of microphonics limiting those two cavities.

INTRODUCTION

The LCLS-II project has recently installed and commissioned 35 1.3 GHz cryomodules (CMs) and 2 3.9 GHz cryomodules at SLAC National Accelerator Laboratory to create a new superconducting linac for the Linear Coherent Light Source (LCLS) [1, 2]. The new superconducting linac will provide 4 GeV electrons for generation of soft and hard X-rays. Each cryomodule contains 8 9-cell TESLA-style elliptical cavities that operate at a nominal accelerating gradient of 16 MV/m.

Microphonics can be a serious issue for superconducting cavities. Small vibrations can cause the cavities to detune (shift the resonance frequency) and if microphonics are large enough there may be insufficient power available to keep the cavity at gradient or the RF controller may not be able to cope with the detuning and lose control of the cavity. Considerable research and development was invested into the LCLS-II cryomodule design to minimize microphonics and ensure a functional linac [3–6]. The design specification for the cryomodules requires that the peak detuning (the largest detune observed during regular operation) be less than 10 Hz for the 1.3 GHz cavities and 30 Hz for the 3.9 GHz cavities. Specifications were met during cryomodule testing, but microphonics have the potential to be worse in the final installed machine. Here we show preliminary microphonics/detuning measurements from the installed LCLS-II cryomodules.

Cryomodule Details

Some details of the cryomodule design are needed to understand the microphonics seen in the cryomodules. The liquid helium vessel and the helium supply circuit are of particular interest to us.

Each cavity in the cryomodule has an individual helium vessel around it. The helium vessel is attached to the "two-phase pipe" via a chimney. The two-phase pipe runs the length of the cryomodule and connects to all 8 cavities. The two-phase pipe does not connect to neighboring cryomodules. The accelerator tunnel has a 0.5% grade, resulting in each cavity having a different "height" of helium above it. Acoustic resonant modes can be excited in these liquid helium vessels.

Liquid helium is supplied to the cryomodule through two main circuits: the Joule-Thomson (JT) valve/line and the Cool Down (CD) valve/line. The JT line and CD line both connect to the helium supply line: a supercritical helium gas line. The JT valve is the helium supply during regular operations and connects to the two-phase pipe. The JT valve is a pneumatic valve and actuates to keep the helium level constant (within tolerances) in the two-phase pipe. Gas (called, "flash") is produced by the JT valve and can drive microphonics. The CD valve/line is used during fast cool down operations of the linac and connects directly to the bottom of each cavity's helium vessel. The CD valve should be closed during normal operations of the linac, but due to the position of the line, leaks through the CD valve could produce significant microphonics. JT valve actuation, flash from the JT valve/line, and leaks through the CD line could produce significant microphonics. We find that CD valve leaks are responsible for unmanageable microphonics in some of our cavities.

Machine Layout

Figure 1 shows detuning of the cavities for the entire linac and a schematic layout of the linac. The superconducting linac is divided into 4 sections: L0B, L1B, L2B, and L3B. L1B contains the 2 3.9 GHz modules (HL's). There are warm beam line sections between each of the superconducting linac sections which contain a variety of equipment which may generate vibrations. In particular, the connection to the cryoplant is located between L2B and L3B, and highway 280 crosses over the accelerator tunnel ≈ 1 km past L3B. Nine insulation vacuum pumps are connected to the cryomodules at locations indicated in Fig. 1.

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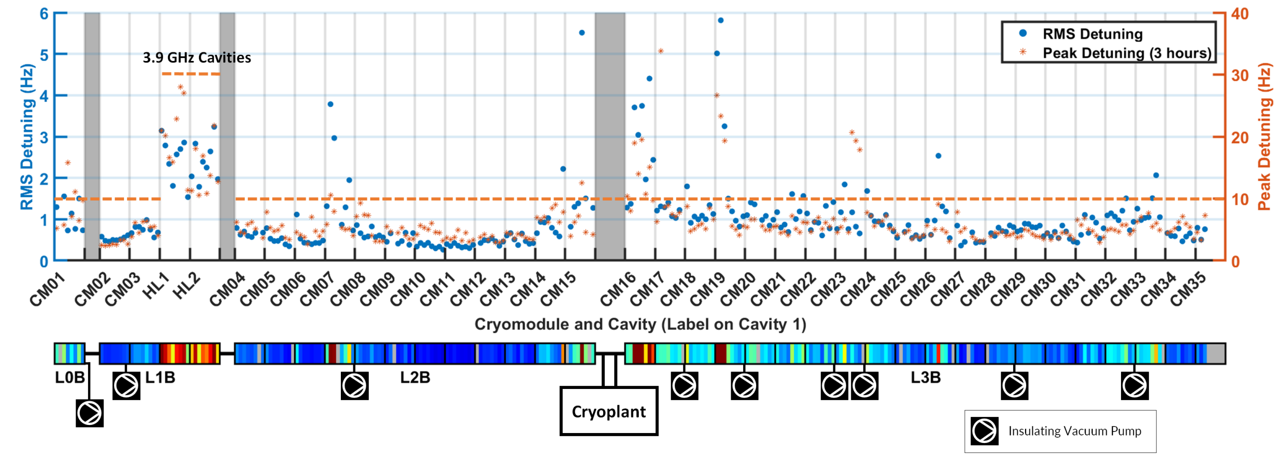


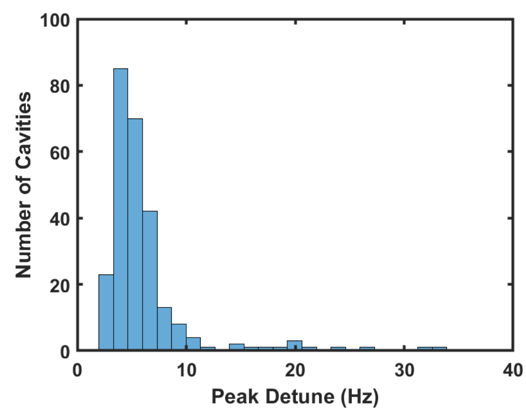
Figure 1: RMS (left axis) and peak detuning (right axis) of the entire superconducting linac. The detuning data was taken over 3 hours at a rate of 500 Hz. Grey rectangles represent gaps between sections of the superconducting linac. Below the plot is a schematic layout of the superconducting linac indicating the section names and locations of insulation vacuum pumps. The layout doubles as a heat map of the linac's microphonics (gray represents inactive cavities). Note that the left (RMS) and right (peak) axes have different scales.

WHOLE MACHINE MICROPHONICS

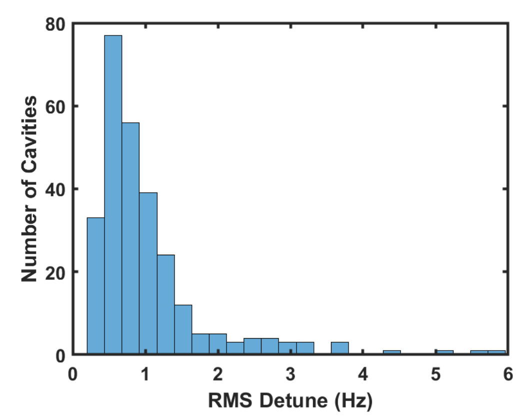
Microphonics measurements have been taken on the entire linac (minus several currently inoperable cavities) on multiple occasions. Figure 1 shows the Root Mean Square (RMS) and peak detuning of the cavities for the entire linac. The detune measurements were taken over 3 hours of operation at a rate of 500 Hz. The linac schematic (Figure 1) shows a heat map of the detuning severity. Figure2 shows histograms of the RMS and peak tuning of the 1.3 GHz cavities. Overall, 94% of the cavities are within the detuning specification, and only two cavities are gradient limited due to microphonics (CM19 cavities 1 and 2 limited to 12 MV/cavity), both due to leaking cool down valves as discussed below.

Frequency mode analysis provides insight into the sources of microphonics. Figure 3 shows the Power Spectral Density (PSD) and a spectrograph of the detuning of a typical cavity and Fig. 4 shows the average PSD over the linac. A 59/60 Hz peak arises from external noise (likely from insulation vacuum pumps). Fundamental modes were seen at 16 Hz and 21.2 Hz with higher order resonances seen at multiples of these frequencies. Similar resonances were seen during cryomodule testing at FNAL [3]. Due to their frequency, these are likely acoustic modes in the liquid helium lines of the cryomodule. During cryomodule testing at FNAL it was seen that these resonances changed frequency depending on the helium pressure. The 16 Hz mode series is seen in L0B, L1B, and L2B, while the 21.2 Hz mode series is seen in L3B because of the slight difference in helium pressure between these two sections.

As with cryomodule testing [7], a mode is observed that is speculated to be a Helmholtz mode[1] in the chimney of the helium vessel. The frequency of the mode varies by cavity depending on the helium liquid level. Since the cryomodules



(a) Histogram of peak detune.



(b) Histogram of RMS detune.

Figure 2: Histograms of a) peak detuning and b) RMS detuning of the 1.3 GHz cavities in the cryomodule. The peak detune specification is 10 Hz.

[1] This mode is akin to blowing across the opening of a jug or bottle.

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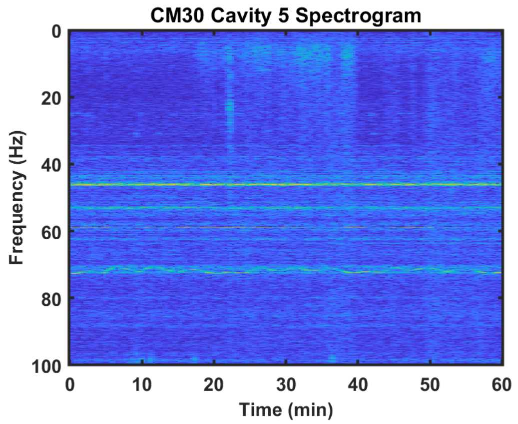
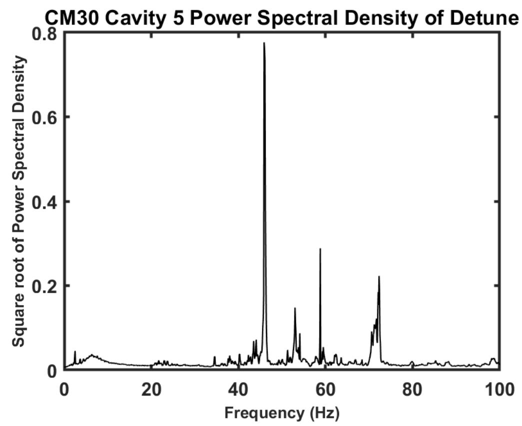
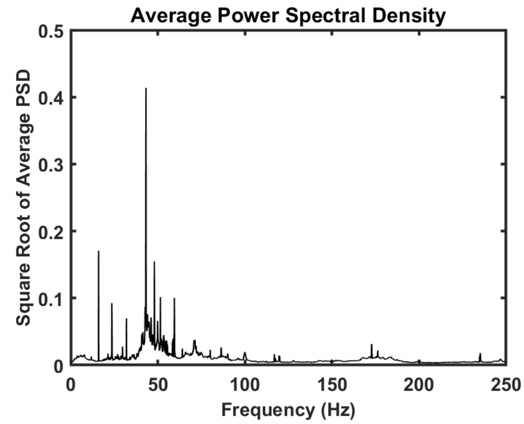


(a) Spectrogram.

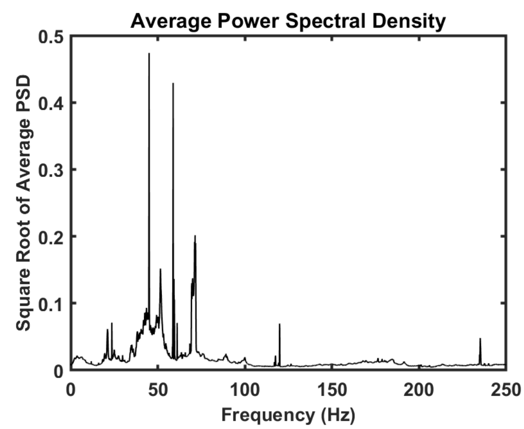


(b) Power spectral density.

Figure 3: An example a) spectrogram and b) power spectral density plot of detune over the course of 1 hour for a cavity in the linac.



(a) Average power spectral density of cavities in sections L0B, L1B, and L2B over a 3 hour measurement.



(b) Average power spectral density of cavities in section L3B over a 3 hour measurement

Figure 4: Average power spectral densities of cavities in two halves of the linac. Each half is fed by a separate distribution box and have slightly different helium pressures which impacts the frequency of certain acoustic modes in the cryomodule.

are on 0.5% grade, the frequency varies between cavities even within the same cryomodule. The mode is seen from roughly 40 to 56 Hz in the linac.

Additional analysis and studies are needed to fully characterize the microphonics. For example, a peak is seen at 23.6 Hz across the entire linac which was not seen during cryomodule testing. The source of this peak is still being investigated.

SOURCES OF MICROPHONICS

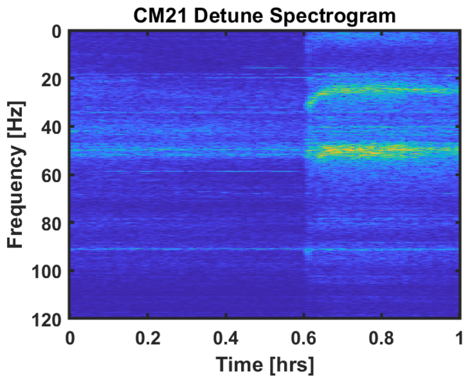
Using our microphonics data, we can identify the main sources of microphonics in our linac. In addition, we can examine some potential microphonics sources that were of concern during the development of the LCLS-II cryomodules.

Valve Regulation

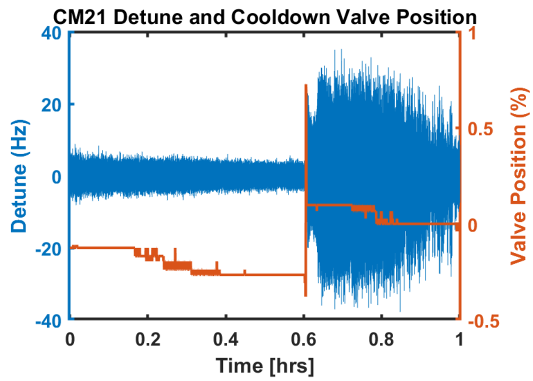
Actuation of the JT valve while regulating the liquid helium level was a cause of concern for the LCLS-II cyromodule. Earlier designs had significant microphonics caused by this, and research and development was conducted to mitigate the impact. In several cryomodules in the linac this was tested by locking the JT valve in position for short periods of time. Microphonics measurement were taken before, during, and after locking the JT valve position and no change in microphonics was observed. In practice, this is not a measurable source of microphonics during regular operation of the linac.

Vacuum Pumps

There are 9 insulation vacuum pumps attached to the cryomodules that are potential sources of microphonics. These pumps are a combination of scroll and turbo molecular pumps hooked up to the cryomodule insulation vacuum at specific points along the linac (see Fig. 1) and are run during operation. The connections are made in such a way as to isolate the vibration of the pumps from the cavities, but some microphonics are still generated. The 59/60 Hz detuning is seen to be worse near vacuum pumps and near the ends of the linac sections, though they remain within specification.



(a) Spectrogram.



(b) Detune and cool down valve position.

Figure 5: Microphonics measured during an event where the cool down valve of a cryomodule opened slightly. a) Shows a spectrogram over the course of the measurement, and b) shows the detune and valve position during the measurement. At 0.6 hours the read back of the valve position increases slightly conincidentally with an increase in the microphonics. Note that the valve position read back can be negative.

Cool Down Valve Leaks

Leaking cool down valves is a major source of microphonics for some cavities (particularly for CM19 cavities 1 and 2). A slight opening of the cool down valve can cause a drastic increase in microphonics. Figure 5 shows microphonics during an incident where an improperly balanced cool down valve slightly opened during operation. The read back of the valve position opens slightly and the peak detuning increases from < 10 Hz to ≈ 30 Hz. At the same time, the temperature of the cool down line, as measured by a thermal sensor on the heater block, plummeted from ≈ 20 K to ≈ 2 K. The problem with this valve was resolved and transients valve opening is not currently an issue, but constant valve leaks are still a problem for some cryomodules.

Though the cool down valves should be closed during normal operation, we find evidence that the cool down valves are leaking for several cryomodules. In the late fall of 2022 CMs 16, 17, 18, and 19 were experiencing sufficiently large microphonics such that the gradient was limited in those cryomodules, particularly cavities 1-4. All four of these cryomodules had cool down lines close to 2 K, while we expect the cool down to be above 10 K during regular operation. Cycling the cool down valve on CM 18 completely fixed the issue, though it did not help the other modules. After another warmup and fast cool down (CD valves fully opened), CM 17 also resolved and the microphonics in CM 16 reduced to a manageable level. This supports that these modules were having issues with leaking cool down valves.

Additional cryomodules in the linac have cool down lines near 2 K but have varying microphonics behavior. Cool down lines that are at ≈ 2 K most likely have a leaking cool down valve. Some cryomodules with cold cool down lines show no increase in microphonics. With a small leak, we expect the superfluid helium to be able to absorb and transport the gas coming from the valve, but at a sufficient flow rate gas bubbles will be pushed through the cool down line driving microphonics. Further studies are needed to fully understand the role of leaking cool down valves in the linac.

CONCLUSION

Initial measurements of the microphonics in the installed LCLS superconducting linac show manageable levels of microphonics. 94% of cavities are within the detune specification (10 Hz for the 1.3 GHz cavities), and only two cavities are currently gradient limited due to microphonics. We understand the major sources of microphonics in the cryomodules and expect to be able to resolve problems with the two gradient limited cavities, which are limited due to microphonics generated by a leaking cool down valve. Some resonances in our cavities require more study to understand, but do not impact the performance of the linac. Overall, microphonics are not an impediment to linac operation for the LCLS superconducting linac.

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