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MEASURING Q_0 IN LCLS-II CRYOMODULES USING HELIUM LIQUID LEVEL

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Abstract

The nitrogen-doped cavities used in the Linac Coherent Light Source II (LCLS-II) cryomodules have shown an unprecedented high Q_0 in vertical and cryomodule testing compared with cavities prepared with standard methods. While demonstration of high Q_0 in the test stand has been achieved, maintaining that performance in the linac is critical to the success of LCLS-II and future accelerator projects. The LCLS-II cryomodules required a novel method of measuring Q_0, due to hardware incompatibilities with existing procedures. Initially developed at Jefferson Lab during cryomodule acceptance testing before being used in the tunnel at SLAC, we use helium liquid level data to estimate the heat generated by cavities. We first establish the relationship between the rate of helium evaporation from known heat loads using electric heaters, and then use that relationship to determine heat from an RF load. Here we present the full procedure along with the development process, lessons learned, and reproducibility while demonstrating for the first time that world record Q_0 can be maintained within the real accelerator environment.

BACKGROUND

Design and Specifications

Commissioned in 2022, LCLS-II has seen the installation of 37 cryomodules into a part of the tunnel at SLAC that previously housed a decommissioned part of the normal conducting accelerator. Each cryomodule was built with eight nitrogen-doped cavities, each of which has both its own electric heater and helium jacket. Each helium jacket connects via a "chimney" to a two-phase pipe that spans the length of the cryomodule. That two-phase pipe has one liquid level sensor on its upstream end, and one on its downstream end. Because the linac was built on a 0.5% grade, the downstream liquid level sensor always reads higher than the upstream liquid level sensor. Both liquid level sensors read out as % full, from 0 to 100.

Standard LCLS-II operation mandates cryogenic support for rapid changes in total linac amplitude, seen by the cryoplant as drastic swings in RF heat load. This support is only possible when the cryoplant can use cavity Q_0s to accurately estimate the power being dissipated by the cavities in order to offset the changes in amplitude by using the cavity heaters. This reliance on Q_0 for our cryogenic control loops, along with potential for Q_0 degradation from trapped flux caused by nitrogen doping, means that we require the ability to measure Q_0 whenever we suspect a change in thermal performance.

Existing Methodology

One of the standard ways to measure Q_0 is to measure the loaded Q (Q_L) and make the approximation that the external Q (Q_{ext}) $\approx Q_0$ in order to use Eq. (1). We are unable to use this method due to the fact that our cavities are very strongly coupled with Q_0 on the order of 10^{10} and Q_L on the order of 10^7, which instead yields the relationship $Q_L \approx Q_{ext}$ [1].

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \tag{1}$$

Another standard method correlates the rate of helium flow in g/s to cavity heat load, but our cryomodule design did not include the mass flow meters necessary for that measurement [2]. Similarly, the fact that cryomodules cannot be isolated due to shared cryo piping means that we cannot use the method that correlates helium pressure to heat load [3].

Instead, Ed Daly from Jefferson Lab proposed trying to correlate rate of helium *evaporation* to cavity heat load during cryomodule acceptance testing at the Low Energy Recirculator Facility (LERF) in 2019 [4].

DEVELOPING THE PROCEDURE

Our new method relies on the following premise: if the heat load stays constant in a cryomodule, the liquid helium should settle into a steady state where its rate of refill equals its rate of evaporation. The system is built such that the Joule-Thomson (JT) valve maintains the downstream liquid level at a steady value; if the heat load stays constant, the JT should eventually reach a steady position. If we were to find that steady state and then manually set the JT valve to that position so that it is only maintaining the liquid level steady for that one very specific heat load, changing the heat load in any way should cause the liquid level to either rise (if the heat load is lowered) or fall (if the heat load is increased).

If the JT can no longer regulate, the helium should evaporate faster with higher heat loads from the cavity. Given that assumption, the proposal was to use the heaters to introduce known heat loads and see if there was a robust relationship

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between rate of liquid level drop ($\frac{dLL}{dt}$) and the amount of heat introduced into the system. If we could represent heat load as a function of $\frac{dLL}{dt}$, we could measure how quickly the liquid level drops when a cavity is running, and then use that function to calculate how much heat it had generated while it was on. That, in combination with the cavity's amplitude, can be used to calculate Q_0.

Defining the Baseline

In order to find the JT valve's steady state position, our first thought was to turn the cavities off, set the cavity heaters to 0 W, and wait for the JT valve to settle. Unfortunately, we discovered that the helium does not evaporate without some minimum amount of added heat, and zeroing all the heaters without any RF heat led to significant overfilling in the cryomodule. We empirically found that 48 W distributed among the cavity heaters was a safe level that allowed the JT sufficient room to regulate. Allowing the control loop to run for about an hour revealed that it does in fact settle into a steady state where neither the JT valve nor the downstream liquid level change more than standard operational noise.

It has thus become the standard to define the baseline as the JT valve position found by the control loop after an hour with the RF off and setting the cavity heaters to 48 W.

Calibration

Per LCLS-II specifications, a compliant cavity would need to be able to stably operate at 16 MV/m with a Q_0 of 2.7×10^{10}. Given those parameters, we decided to focus on heat loads between 0 W and 25 W in order to capture both low-gradient/low-heat cavities and cavities that had a Q_0 as low as 1×10^{10}. Of note, we apply all measurement heat loads *on top of* the baseline 48 W, such that a desired heat load δ W corresponds to a cryomodule heater setpoint of $48 + \delta$ W. The results are show in Fig. 1.

The first thing we saw was that there is a very clear linear relationship between heat load and rate of liquid level evaporation. We used standard linear regression to find a "calibration curve" that represented $\frac{dLL/dt}{P_{diss}}$, and then subtracted out the y intercept as a heat load correction such that the line would always intersect the origin (0 W should correspond to no change in helium liquid level).

The early low heat load calibrations took a minimum of five hours and had heat load corrections as high as 50 W. However, we noticed that the time required for a measurement, the required heat load correction, *and* the line fit errors all decreased as the heat loads increased. This was validated further by running a test that spanned 8 W to 80 W, shown in Fig. 2.

Given that information, we decided to pivot from measuring the heat loads expected of a single cavity to instead measuring the heat load expected of an entire cryomodule. As of June 2023, those higher heat loads allow us to complete a full calibration in as little as an hour with heat load corrections as small as 1×10^{-2} W.

RF Measurement

Effective Q Unfortunately, the standard Q_0 is not meant to describe more than one cavity, so our new method required defining what we now call the *effective* Q, or Q_{eff}, such that:

1. For each individual cavity at gradient E_i, the Q_{eff} yields that cavity's dissipated power
$$P_i = \frac{E_i^2 L^2}{[\frac{R}{Q}]Q_{eff}}. \tag{2}$$
2. The sum of all cavities' dissipated power equals the power dissipated by the entire cryomodule
$$P_{tot} = \sum_i P_i = \frac{1}{[\frac{R}{Q}]Q_{eff}} \sum_i E_i^2 L^2. \tag{3}$$

Rearranging Eq. (3) then yields
$$Q_{eff} = \frac{\sum_i E_i^2 L^2}{[\frac{R}{Q}]P_{tot}}. \tag{4}$$

Taking Data After a few measurements, we realized that the calculated heat load would change rather drastically depending on which calibration we used and how long it had been since that calibration had been taken. We decided to add an extra heater-only measurement after each RF measurement in order to quantify that drift as a heat load offset; if the heaters were run at x W but the original calibration associated that $\frac{dLL}{dt}$ with $x + \epsilon$ W, we then add ϵ to the heat that was calculated from the RF measurement as a way to try to make the method more calibration agnostic. This is shown in Fig. 3.

Extracting Single Cavity Heat Loads A fairly recent addition to the method involves taking repeated cryomodule measurements with a different cavity off each time and then using simple matrix math to extract the single cavity heat loads. This is time intensive so we only do it as needed, but the limited applications have proven promising thus far. Equation (5) explains the process where Eq. (5a) is the heat loads calculated with all cavities except cavity i on, Eq. (5b) is the heat load from each cavity alone, and Eq. (5c) is the on/off status of each cavity during a measurement. Eq. (5d) can then be rearranged as Eq. (5e).

$$\overline{P} = \begin{bmatrix} \overline{P_0} \\ \vdots \\ \overline{P_i} \end{bmatrix} \tag{5a}$$

$$P = \begin{bmatrix} P_0 \\ \vdots \\ P_i \end{bmatrix} \tag{5b}$$

$$M = \begin{bmatrix} 0 & 1 & 1 & \dots & 1 \\ 1 & 0 & 1 & \dots & 1 \\ 1 & 1 & 0 & \dots & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & 1 & \dots & 0 \end{bmatrix} \tag{5c}$$

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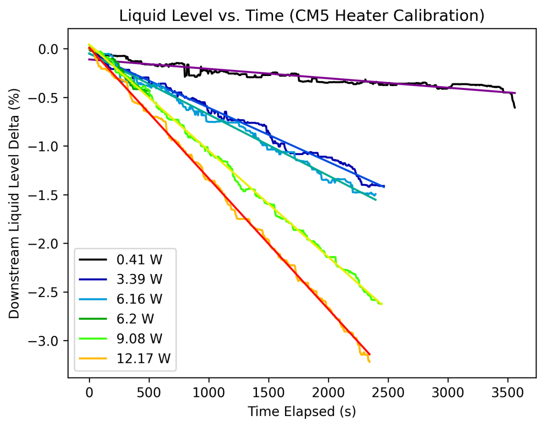
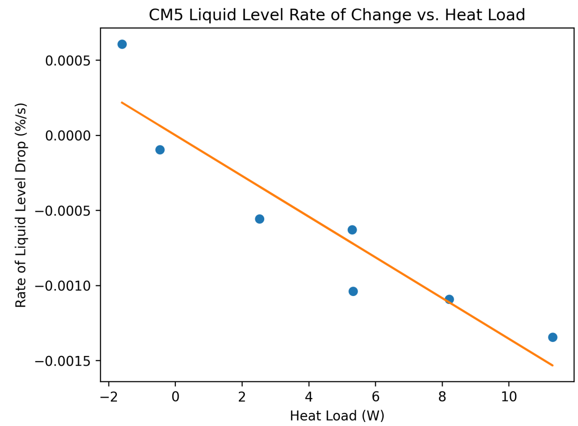
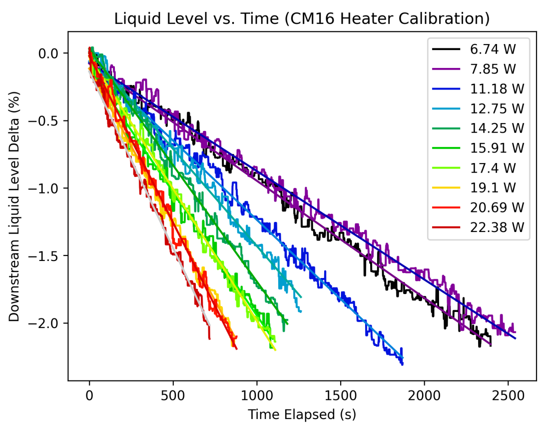


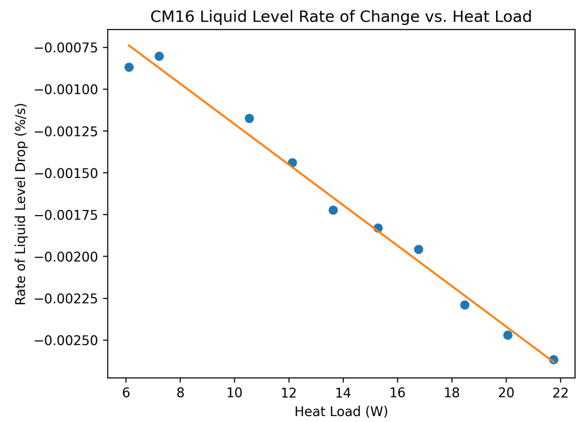
(a) Liquid level drops from sub 12 W



(b) Line fit of sub 12 W liquid level drops

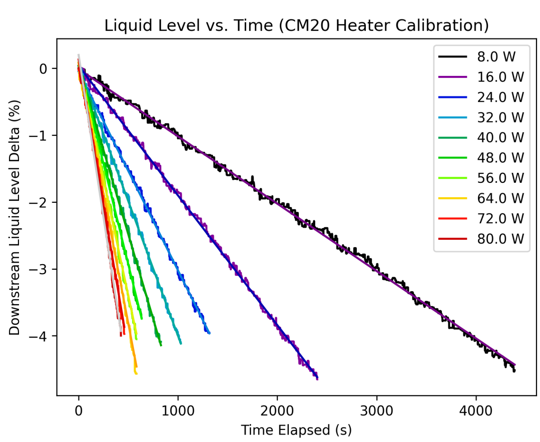


(c) Liquid level drops from 6 W to 22 W

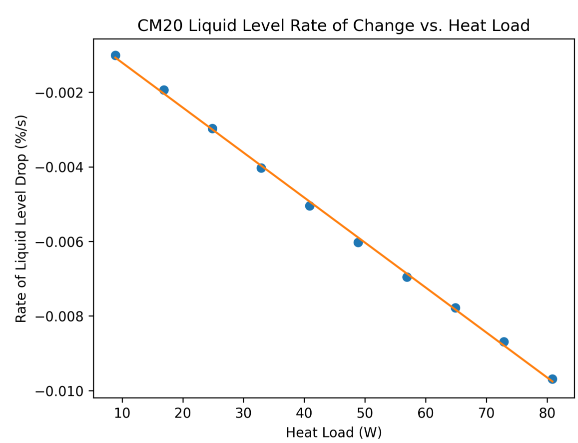


(d) Line fit of 6 W to 22 W liquid level drops

Figure 1: Liquid level drop data from 0 W to 22 W.



(a) Liquid level drops from 8 W to 80 W



(b) Line fit of 8 W to 80 W liquid level drops

Figure 2: Liquid level drop data from 8 W to 80 W.

$$MP = \overline{P} \tag{5d}$$

$$P = M^{-1}\overline{P} \tag{5e}$$

Of note, cavities dissipating below 4 W seem to fall within the noise of the measurement and calculation results in heat loads with very high error bars.

Automation

As of June 2023, this method has been fully automated such that the only manual steps left are:

- Coordinating with the cryoplant staff to obtain control of the cryomodule to be measured
- Finding the stable JT valve position for 48 W

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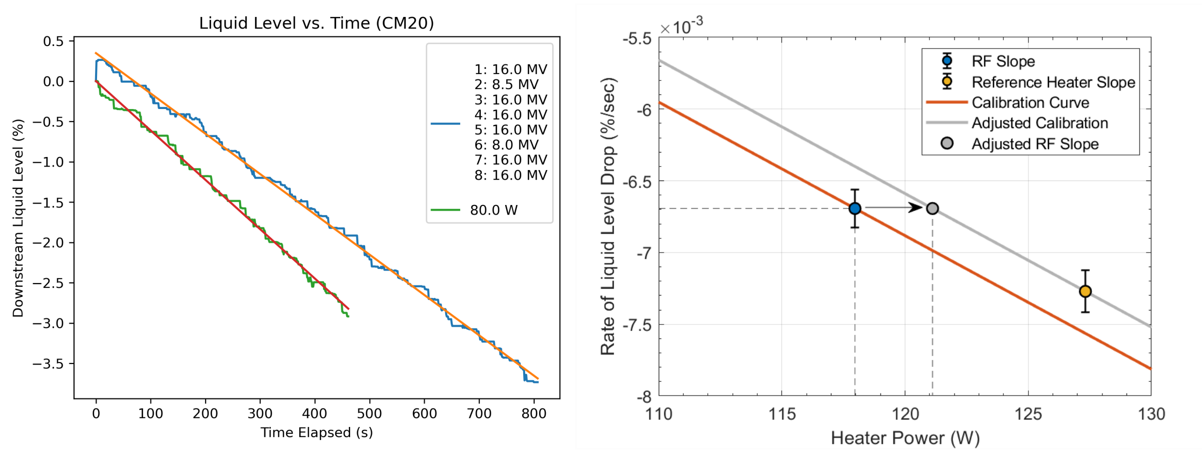

(a) RF measurement with 80 W heater calibration

(b) Shifting calibration curve

Figure 3: Full CM measurement and resulting calibration adjustment.

The process has proven to be very robust, and the hope is to be able to automate the position finding in the future.

Error

Our error analysis shows that we can expect errors on the order of 15-20%, largely from early line fit errors that get propagated into additional line fits later on. This method is also extremely susceptible to changes in heat load during the measurements, such that helium pressure oscillations sometimes observed in the linac can drastically impact the rate of liquid level drop and skew the final calculation.

Results

After doing a measurement of each cryomodule installed in the linac at SLAC, we observed an average machine Q_0 of 2.8×10^{10} as shown in Fig. 4. This exceeded the specification of 2.7×10^{10} and validated the use of nitrogren doping as a way to achieve high Q_0 in an installed linac.

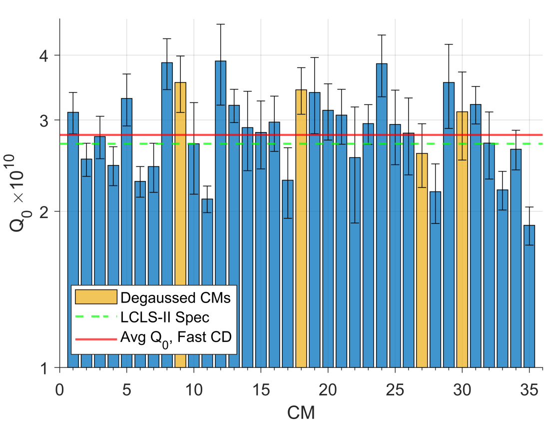

Figure 4: The average measured Q_0 of 2.8×10^{10} exceeded specification of 2.7×10^{10}.

One of the reasons for the difference in Q_0 across the cryomodules is difference in amount of trapped magnetic flux. We were given the time to degauss [5] two of the worst performers before RF commissioning, and those measured two of the highest Q_0s in the first round of measurements. Heartened by those results, we were given the time to degauss another two cryomodules during a scheduled downtime and saw the dramatic increase in Q_0 shown in Table 1. This validation of the benefits of degaussing has strengthened the case for it being a standard part of cryomodule installation.

For instances where it seems like there is atypically large Q_0 variation *within* a given cryomodule, we have also shown that we can extract individual cavity heat loads with good resolution above 4 W. Table 2 shows an example of this extraction with two cavities that fall within the noise of the measurement.

Table 1: Effects of Degaussing

Cryomodule	Q_0 Before Degauss	Q_0 After Degauss	P_{diss} Savings (16 MV/m)
CM18	1.3×10^{10}	3.4×10^{10}	104 W
CM27	1.0×10^{10}	2.6×10^{10}	134 W

Table 2: CM 28 Single Cavity Extraction Using Eq. (5)

Cavity	Measured $\overline{P}$ (W)	Extracted P (W)	$E_{acc}L$ (MV)	Q_0
2	52.5	11.6	16.6	2.4×10^{10}
3	51.2	12.9	16.6	2.1×10^{10}
4	53.1	11.0	16.6	2.5×10^{10}
5	61.3	2.8	10.3	3.7×10^{10}
6	53.1	11.0	16.6	2.5×10^{10}
7	61.5	2.6	16.6	1.1×10^{11}
8	51.9	12.2	15.6	2.0×10^{10}

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We experienced a spontaneous stress test of the calculated Q_0s during RF commissioning when an error in the Personnel Protection System led to a sudden revocation of all RF permits. This took us from full to no amplitude near instantaneously - a drop of about 3.5 GV. While we had expected such a dramatic decrease in dynamic heat load to trip the cryoplant, the heater compensation system was able to use the Q_0s we had calculated to convert the lost RF heat into electric heat such that the cryoplant managed to absorb the change and stay on. This experience cemented our confidence in full cryomodule measurements as a good approximation for individual cavity heat load.

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This work would not have been possible without Ed Daly's original idea and the hard work of the original Jefferson Lab team working with us at LERF. There were also many SLAC accelerator operators who helped to take measurements without whom we might not have been able to take all the data we needed in the time we had allocated to us. This work was funded by DOE contract Nos. DE-AC02-76SF00515.

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