ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-TUPO058

COOL DOWN STUDIES FOR THE LCLS-II PROJECT*

M. Ge†, M. Liepe, J. Sears, CLASSE, Cornell University, Ithaca, New York, USA
D. Gonnella, SLAC National Accelerator Laboratory, Menlo Park, California, USA

Abstract

The quality factor of the nitrogen-doped SRF cavities for the LCLS-II project are strongly impacted by cool down speed. A sufficiently fast cool down speed can produce large thermal gradient across a cavity and sufficiently expel magnetic flux when the cavity wall passes from the normal-conducting to the superconducting state. However, instrumentation in LCLS-II production cryomodules has been kept at a minimum, and additional information during the cool down of the modules is therefore desirable. In this work, we study if and how RF data can be used during cavity cool-down to determine the transition speeds of the individual cavities in the LCLS-II linac.

INTRODUCTION

The LCLS-II project requires an average unloaded quality factory Q_0 for the 1.3 GHz SRF cavities of 2.7×10^{10} at an operating temperature of 2K and accelerating gradient of 16 MV/m [1]. The 2N/6 nitrogen doping recipe (2 min N-doping at 800C followed by a 6 min anneal at 800C) [2, 3] has been chosen for the surface preparation of the LCLS-II SRF cavities, However, the quality factor of nitrogen doped SRF cavities are strongly impacted by cool down speed [4] due to their high sensitivity to losses from trapped magnetic flux [5].

New cool down studies on a single-cell cavity were conducted with the goal of developing a means of measuring cool down rate of SRF cavities using RF methods when temperature sensors are not available, such as in the LCLS-II cryomodules. A single-cell cavity was provided by LCLS-II for these studies. This cavity was reset using EP at Cornell, and then given the standard 2/6 nitrogen-doping that LCLS-II production cavities receive. The cavity was tested at Cornell on a test insert fitted with a variable coupler that could reach Q_{ext} close to 4×10^7, the Q_{ext} required by the LCLS-II project for cavities assembled in cryomodules.

32 cool downs of the cavity were completed in total. The goal of these cool downs was to determine

1. If it is possible to identify cool down rate and/or gradient by means of the transition time of the cavity as measured on a network analyzer
2. If 1. is affirmative, define a model which from a given transition time predicts the cool down rate and/or gradient of a cavity in the cryomodules during linac cooling.

* Work supported by the US DOE and the LCLS-II project.
† mg574@cornell.edu.

METHOD

A single-cell cavity was cooled in a vertical test Dewar multiple times, with different cool down rates and gradients. A picture of the cavity on the test stand is shown in Figure 1. Temperature sensors were placed on the cavity, two on the equator, and two on each of the irises. The Q_{ext} of the input coupler was set to $\sim4\times10^7$. A network analyzer was connected to the forward and transmitted power connections on the cavity and an S_{21} measurement was taken during cool down. The parameters for the network analyzer measurement are given in Table 1.

Figure 1: Test insert with single-cell cavity and instrumentation.

Table 1: Network Analyzer Parameters

Parameter	Value
Center	Resonance f_0 at starting temp, re-centered after each scan
Span	100 kHz
IF Bandwidth	100 Hz
Forward Power	~10 W

From an S_{21} measurement, the loaded quality factor Q_L of the cavity can be calculated,

$$Q_L = \frac{f_0}{\Delta f}, \quad (1)$$

where f_0 is the resonance frequency of the cavity (peak on the network analyzer) and Δf is the width of the resonance

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-TUPO058

curve at the points 3 dB below the maximum. Q_L is related to the intrinsic cavity Q, Q_0 by

$$\frac{1}{Q_L} = \frac{1}{Q_{ext}} + \frac{1}{Q_0}. \quad (2)$$

When the cavity is normal conducting, Q_0 is ~1×10^4-5×10^4, heavily dominating Q_L, resulting in a direct measurement of normal conducting Q_0 with the network analyzer. When the cavity is superconducting, Q_0 is significantly higher than Q_{ext} and Q_L is very close to Q_{ext}. In reality, due to cavity microphonics, the network analyzer measurement could not resolve Q's above 10^7, so some saturation occurred when the cavity transitioned. An example S_{21} measurement comparing normal and superconducting states is given in Figure 2.

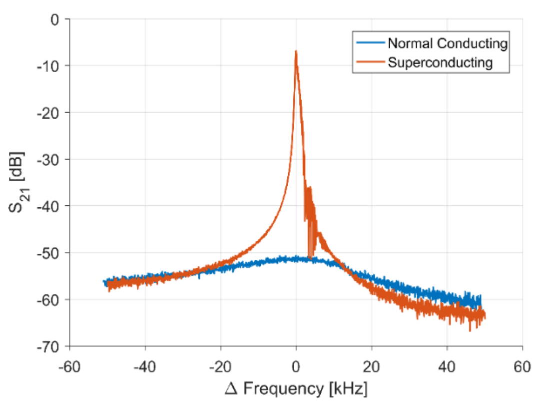

Figure 2: Example of normal and superconducting states on the network analyzer.

From the network analyzer traces, Q_L can be determined. For a given cool down, many traces are taken. Figure 3 shows two measurements of Q_L vs time, first for a fast cool down, and second for a slow cool down. The beginning of the superconducting transition is clearly visible. We then define a transition time as the time it takes for the cavity to go from Q_L of 1×10^5 to 2×10^6 (corresponding to ~50% and ~97% of the cavity being superconducting, respectively). It is clear from Figure 3 that this transition time is quite different in the two cases.

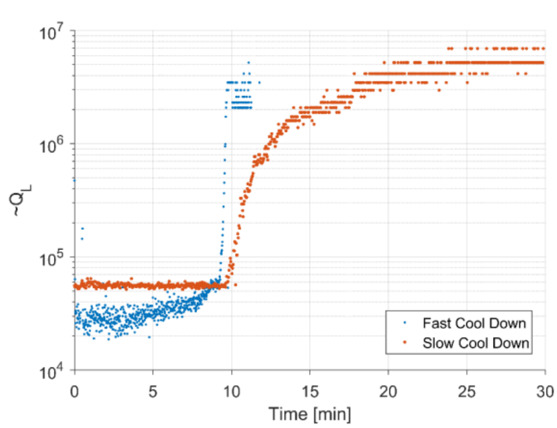

Figure 3: Example Q measurement for two cool downs.

RESULTS

A total of 32 cool downs were completed with different cool down rates and spatial temperature gradients at T_c. These parameters were controlled by varying the starting temperature of the cool down, helium flow rate, and heat applied to the incoming helium gas through the use of a "slow cool down helium transfer line" affixed with resistive heaters in the helium path. For each cool down, transition time, cool down rate, and cool down gradient were measured via the temperature sensors located on the cavity and S_{21} measurements.

The transition time of the cavity versus cool down rate is shown in Figure 4. The data has been colored according to "fast" (temperature gradient $\Delta T > 3K$ across the cavity) or "slow" ($\Delta T < 3K$) cool downs for ease of discussion. For cool downs with small spatial temperature gradients (shown in orange) we can see that there is a clear exponential decrease of transition time as the cool down rate is increased i.e. with faster cool down, the cavity transitions faster. However, at large spatial temperature gradients ($\Delta T > 3K$), the results show no clear trend.

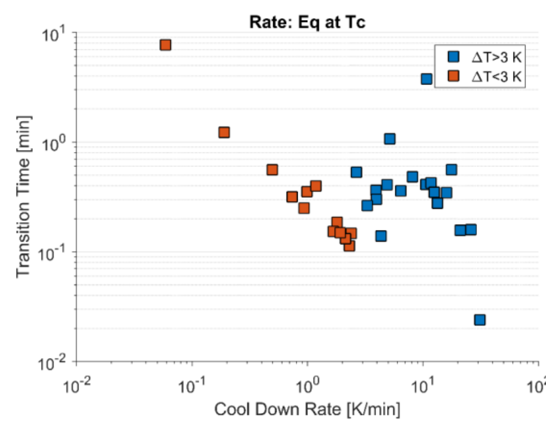

Figure 4: Transition time vs cool down rate.

Looking at the cool down gradient however sheds light on the high gradient region. The transition time of the cavity versus cool down gradient at T_c is shown in Figure 5. We can identify three important regions:

- At very small cool down gradients, the transition time decreases as the gradient is increased. This is in line with the results shown in Figure 4, where faster cool downs (usually accompanied by large spatial temperature gradients) led to shorter transition times.
- At very large gradients, as the gradient is increased, transition time also increases. This suggests that when a cavity begins transitioning with a large spatial gradient, the time it takes for the top of the cavity to become superconducting slows down the overall transition, even though the rate of cool down is quite high.
- Between these two regions there is an intermediate region, where the transition time is relatively constant with increasing cool down gradient. This is due to partial compensating impacts of the increasing

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-TUPO058

temperature gradient and increasing cool down speed on the transition time.

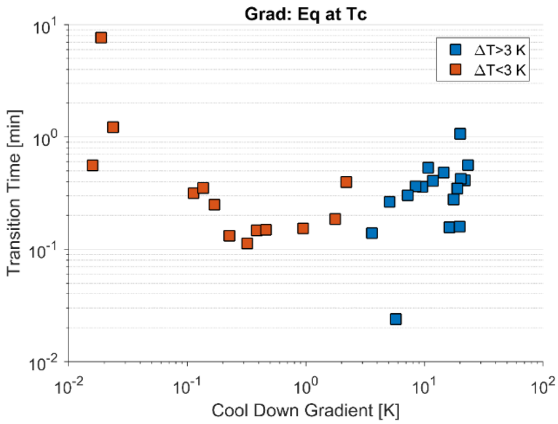

Figure 5: Transition time vs spatial cool down gradient across the cavity cell.

DISCUSSION

What we can see from these results is that two effects play a role in the time it takes for the cavity to transition from normal to superconducting. First, faster cool down results in shorter transition times. This was expected prior to the experiment. However, as the cool down gets faster, typically the spatial temperature gradient at T_c also gets larger. This results in the transition time getting longer again at very fast cool downs, since when the bottom of the cavity begins transition, the top is at a significantly warmer temperature, ultimately increasing the transition time.

This initial analysis suggest that it is not straightforward to use RF measurements to characterize a cavity's cool down gradient in the linac, though further analysis of the experimental data is planned for the future and might result in additional insights. LCLS-II cool downs will be in the large gradient regime, thus likely in the region on the right side of Figure 4, where there is not a clear trend in the data. Moreover, using the transition time analysis, it impossible to distinguish between cavity cool downs with very large and very small gradients as shown in Figure 5.

Work is still underway to completely understand the mechanics behind counteracting effects of the temperature gradient and the cool down speed. Ideally, a model could be developed and fit to the data, however this has not yet been completed. Additional analysis could also lead to a better separation of the cool down rate and gradient. Conducting fast cool downs with very small spatial temperature gradients, or vice-versa could be useful in the future to better understand cool down dynamics.

REFERENCES

[1] LCLS-II Final Design Report, https://portal.slac.stanford.edu/sites/ad_public/people/galayda/Shared_Documents/FDR.pdf

[2] A. Grassellino, A. Romanenko, D. Sergatskov, O. Melnychuk, Y. Trenikhina, A. Crawford, A. Rowe, M. Wong, T. Khabiboulline, and F. Barkov, "Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures", *Superconductor Science and Technology*, vol. 26, no. 10, p. 102001, 2013.

[3] D. Gonnella, S. Aderhold, A. Burrill, E. Daly, K. Davis, A. Grassellino, C. Grimm, T. Khabiboulline, F. Marhauser, O.Melnychuk, A. Palczewski, S. Posen, M. Ross, D.Sergatskov, A. Sukhanov, Y. Trenikhina, K.M. Wilson, "Industrialization of the nitrogen-doping preparation for SRF cavities for LCLS-II", *Nucl. Instr. Meth.*, vol. 883, pp. 143-150, 2018.

[4] A. Romanenko, A. Grassellino, O. Melnychuk, D.A. Sergatskov, "Dependence of the residual surface resistance of SRF cavities on the cooling rate through Tc", *J. Appl. Phys.*, vol. 115, p. 184903, 2014.

[5] D. Gonnella, J. Kaufman, M. Liepe, "Impact of nitrogen doping of niobium superconducting cavities on the sensitivity of surface resistance to trapped magnetic flux", *J. Appl. Phys.*, vol. 119, p. 073904, 2016.