COOL DOWN AND FLUX TRAPPING STUDIES ON SRF CAVITIES*

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Abstract

Recent results from Cornell and FNAL have shown that cool down rate can have a strong impact on the residual resistance of a superconducting RF cavity during operation. We have studied the effect of cool down rate, gradient, and external magnetic field during cool down on the residual resistance of an EP, EP+120°C baked, and nitrogen-doped cavities. For each cavity, faster cool down and large gradient resulted in lower residual resistance in vertical test. The nitrogen-doped cavities showed the largest improvement with fast cool down, while the EP+120°C cavity showed the smallest. The cavities were also placed in a uniform external magnetic field and residual resistance was measured as a function of applied field and cool down rate. We show that the nitrogen-doped cavity was the most susceptible to losses from trapped flux and the EP+120°C cavity was least susceptible. These measurements provide new insights into understanding the physics behind the observed impact of cool down rates and gradients on the performance of cavities with differing preparations.

INTRODUCTION

New light sources such as the SLAC Linac Coherent Light Source II (LCLS-II) require the operation of SRF cavities in CW mode [1]. In order to achieve this, the cavities must have a very high intrinsic quality factor (Q_0). A major limitation on cavity performance is the ambient magnetic field present in the vicinity of the cavity during cool down through T_c. When a material transitions from normal conducting to superconducting, some of hte ambient field gets trapped in the superconductor, causing RF losses [2]. Importantly, the cool down procedure has also been shown to have a strong effect on cavity performance [3–5]. It is therefore important to understand the effect of magnetic field and cool down procedure on cavity performance in order to properly design cryomodules for future machines. Previously a study at Cornell showed that nitrogen-doped cavities are much more susceptible to increased residual resistance from trapped magnetic field and slow cool down than standard EP and 120°C baked cavities [3]. This paper discusses an expansion of this previous study in which 6 additional cavities (for a total of 8) were studied. In total, 6 nitrogen-doped cavities, an EP cavity, and an EP+120°C baked cavity were studied. These measurements provide new insights into the susceptibility to RF losses from trapped flux and its significant dependence on cavity surface preparation.

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Figure 1: The experimental setup showing cavity, coil for applying magnetic field, fluxgate magnetometers, and temperature sensors.

EXPERIMENTAL METHOD

Seven single-cell 1.3 GHz ILC shaped cavities were prepared with different methods. Five of them (constructed at Cornell) were prepared with nitrogen-doping in the method outlined in [6]. The sixth cavity was prepared with nitrogen-doping at FNAL (heat treatment at 800°C in vacuum followed by 20 minutes in 20 mTorr of nitrogen followed by an additional 30 minutes in vacuum and finally a 7 μm final EP). The seventh cavity was first prepared with EP and 120°C bake and then retreated with just final EP but no 120°C bake. Each cavity was cooled through T_c in a variety of applied uniform external magnetic fields and with different cool down rates. The equipment and method is outlined in [3]. A picture of the experimental setup is shown in Fig. 1. The cavities were surrounded by a coil for applying magnetic field and affixed with three temperatures sensors, one on the bottom flange, one on the equator, and one on the top flange. A fluxgate magnetometer was also affixed to the iris just above the cell for measuring applied field and trapped flux. For each cavity and each cool down, cool down rate and gradient over the cavity were measured in addition to the trapped flux from the external field and the residual resistance (extracted from Q_0 vs temperature data with SRIMP [7]).

EFFECT OF EXTERNAL FIELD

For each cavity and cool down, the applied magnetic field and cool down rate was tuned. By adjusting these parameters, the amount of trapped flux could also be tuned. Figure 2 shows the measured residual resistance as a function of trapped magnetic flux for all eight cavities. Also included is a linear fit for each cavity. We can see that the EP and EP+120°C bake cavities have significantly less susceptibility to residual losses from trapped flux than the six nitrogen doped cavities. Moreover, the more doped a nitrogen-doped

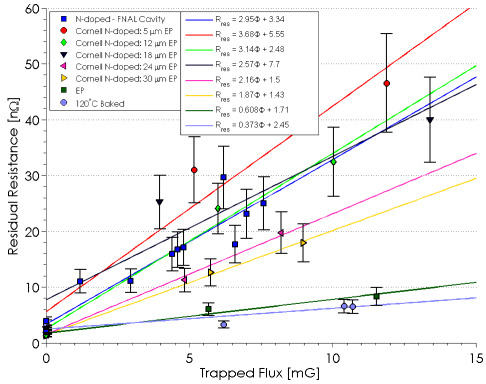

Figure 2: Residual resistance as a function of trapped flux. The amount of flux trapped in the cavity walls depends on both applied field and cool down rate (gradient) [3].

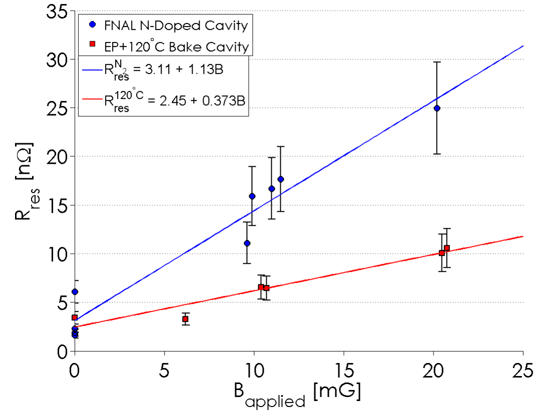

Figure 4: Residual resistance vs applied magnetic field under fast (>1 K/min) cool down conditions.

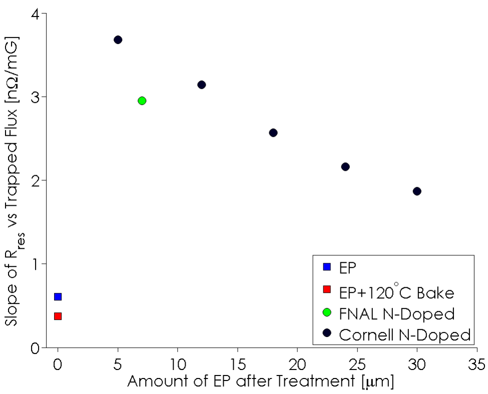

Figure 3: Slope of linear fit from Fig. 2 as a function of final EP after treatment. The FNAL cavity was given a nitrogen doping at a lower pressure than the Cornell cavities, giving it a lower N-doping level and thus a lower susceptibility to trapped flux for the same final EP.

cavity is, the more susceptible it becomes to losses from trapped flux. This becomes evident from the analysis shown in Fig. 3, in which the normalized RF losses from trapped flux (slope of linear fits in Fig. 2) are shown as a function of final EP amount after the doping for the nitrogen-doped cavities. In addition, the susceptibilities for the two un-doped cavities are shown. We can clearly see that the EP and EP+120°C bake cavities have a much lower slope than all of the nitrogen doped cavities. Additionally, for the Cornell nitrogen-doped cavities, more material removal (less doping) gives less susceptibility to residual losses from trapped flux. The FNAL cavity was given a nitrogen-doping in a lower pressure than the Cornell cavities; therefore one can expect it to be less doped for the same amount of material removal. The measured lower susceptibility of this cavity to losses from trapped flux is thus consistent with other data shown in Fig. 3.

The amount of trapped flux greatly depends on the cool down rate, gradient, and external magnetic field [3]. However, if we look at similar cool down rates (10 K/min > dT/dt >1 K/min) we can see that again there is a strong dependence of residual resistance on cavity preparation. Figure 4 shows the residual resistance as a function of external applied magnetic field for the FNAL nitrogen-doped cavity and the EP+120°C baked cavity under fast cool down. We can clearly see that the amount of residual resistance obtained at the same external field is about 3 times higher for the nitrogen-doped cavity than the EP+120°C baked cavity. This is in agreement with the difference in susceptibility to RF losses from trapped flux of these cavity as shown in Fig. 3, meaning that both cavities trap about the same fraction of the ambient magnetic field under similar cool-down conditions, which will then generate larger RF losses in the N-doped cavity surface layer.

EFFECT OF COOL DOWN RATE AND SPATIAL TEMPERATURE GRADIENT

As discussed above, the dynamics of cool down have been shown to have a strong impact on the fraction of ambient magnetic field getting trapped in the cavity walls and thus residual resistance. Because of the difficulty in separating rate and temperature gradient over the cavity during cool down, it is challenging to claim which parameter is more important for reducing pinning of magnetic flux when the cavity transitions from normal conducting to superconducting. Figure 5 shows the residual resistance normalized to the external magnetic field as a function of cool down rate while Fig. 6 shows the same normalized residual resistance as a function of temperature gradient over the cavity when it starts to transition into the superconducting state. We can see that both faster cool down and larger gradient appear to lead to smaller residual resistance in all cavities. However, since in vertical tests faster cool downs also give larger spatial temperature gradients, it is impossible to deconvolute the importance of these two cool-down parameters for reducing flux trapping. Fortunately, recent results from the Cornell Horizontal Test Cryomodule (HTC) allow for separating out

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Table 1: Summary of Cool Down Dynamics for the Cornell HTC [8]

Cool Down	$\frac{dT}{dt}$ **[K/min]**	ΔT_{cavity} **[K]**	Maximum Q_0 (2.0 K)	R_{res} **[nΩ]**
Fast 1	5	5	2.8×10^{10}	5 ± 1
Fast 2	7	3	2.8×10^{10}	4.0 ± 0.8
Slow 1	0.04	0.3	2.5×10^{10}	5 ± 1
Fast 3	5	20	3.2×10^{10}	2.7 ± 0.5

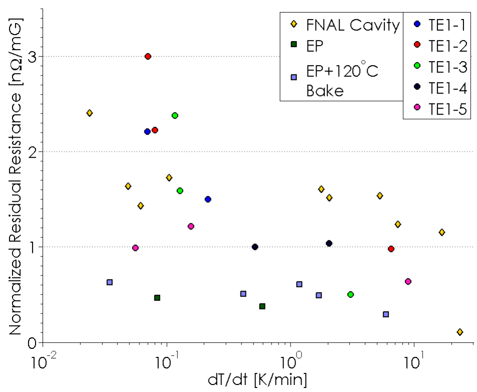

Figure 5: Residual resistance normalized to the external field as a function of cool down rate through T_c for the eight cavities.

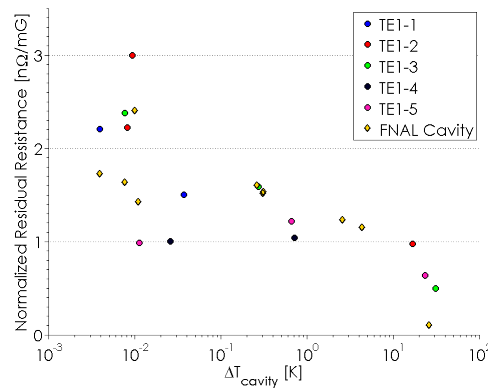

Figure 6: Residual resistance normalized to the external field as a function of temperature gradient across the cavity when it transitions from normal to superconducting for the eight cavities.

the impact of spatial gradients and cool down rate and shown that a larger gradient over the cavity during cool down is far more important to reduce pinning of magnetic flux than cool down rate [8]. Table 1 shows the results from the HTC test for four different cool downs. It is clear from the table that slow cool down gives poor Q performance, while fast cool down gives better results. More importantly, for similar cool down rate, but different temperature gradient across the cavity during cool down, larger gradient gives significanlty better Q performance than smaller gradient. Upon closer inspection of Fig. 6, we can see that below a certain gradient (∼ 5 K), there is not a clear trend of decreasing residual resistance with increasing gradient. However, at higher gradients a clear trend starts to form. We claim that a large gradient above a certain threshold is required to begin to de-pin flux. Cool down rate appears to have a strong effect on residual resistance because a large gradient usually accompanies a faster cool down rate. Therefore, combining the results from these single-cell results with results from the HTC [8], we can claim that the most important cool down parameter is the gradient across the cavity when it transitions from the normal to superconducting state.

CONCLUSIONS

The effects of external magnetic field and cool down dynamics on SRF cavity performance have been discussed for a variety of cavity preparations. We have shown that nitrogen-doping causes a higher susceptibility to RF losses trapped flux than standard EP or EP+120°C bake preparation. Moreover, the more nitrogen-doping a cavity receives, the higher its susceptibility to trapped flux losses. With additional material removal, this effect decreases. Under the same cool down conditions therefore, nitrogen-doped cavities show a residual resistance that is 3 times higher for a given external magnetic field than EP+120°C baked cavities. We have also shown along with [8] that a large temperature gradient during cool down is most important for minimizing trapping of magnetic flux during cool down. In order to achieve the lowest residual resistance, obtaining a larger temperature gradient is thus more important than a faster cool down.

Future work will focus on continuing to study the effect of cool down rate and gradient on de-pinning of magnetic flux, specifically in a full cryomodule. This work serves as an important step in understanding how best to cool down a cryomodule in a machine to achieve the lowest residual resistance and thus the highest quality factor.

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REFERENCES

[1] J.N. Galayda. The LCLS-II project. In *Proceedings of IPAC 2014*, Dresden, Germany, 2014.

[2] *RF Superconductivity for Accelerators*. Wiley, 1998.

[3] D. Gonnella et. al. Flux trapping in nitrogen doped and 120C baked cavities. In *Proceedings of IPAC 14*, Dresden, Germany, 2014.

[4] A Romanenko, A Grassellino, O Melnychuk, and D A Sergatskov. Dependence of the residual surface resistance of SRF cavities on the cooling rate through Tc. *ArXiv*, pages 1–6, 2014.

[5] Julia Vogt, Oliver Kugeler, Jens Knobloch, and Helmholtz-zentrum Berlin. Quest for High Q0: residual Resistance Elimination. In *SRF 2013*, September 2013.

[6] D. Gonnella et. al. Nitrogen treated cavity testing at cornell. In *Proceedings of LINAC 14*, Geneva, Switzerland, 2014.

[7] J. Halbritter. Fortran-program for the computation of the surface impedance of superconductors. *KAROLA Externer Bericht*, (3/70-6), 1970.

[8] D. Gonnella et. al. Nitrogen-doped 9-cell srf cavity performance in the cornell horizontal test cryomodule. In *Proceedings of LINAC 14*, Geneva, Switzerland, 2014.

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