ANALYSIS OF BCS RF LOSS DEPENDENCE ON N-DOPING PROTOCOLS*

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Abstract

We present a study on two parallel-path SRF cavities (one large grain and one fine grain, 1.3 GHz) which seeks to explain the correlation between the amount of nitrogen on the inner surface of a "nitrogen doped" SRF cavity and the change in the temperature dependant (packaged into term BCS) RF losses. For each doping/EP, the cavities were tested at multiple temperatures (2.0 K to 1.5 K in 0.1 K steps) to create a Q_0 vs. E_{acc} vs. T matrix which then could be used to extract temperature dependant and independent components. After each test, the cavities were thermally cycled to 120 K and then re-cooled and retested to assess if evidence of hydrogen migration might appear even at a small level. In addition, TD-5 was also tested at fixed low field (Q_0 vs. T) to fit standard BCS theory. In parallel, SIMS data was taken on like-treated samples to correlate the amount of nitrogen within the RF surface to the change in the temperature dependant fitting parameter "A".

INTRODUCTION

During the last one and a half years, while developing guidance for the nitrogen doping protocols for the LCLS-II cryomodules, JLab has systematically doped over 20 single and multi-cell cavities, with most cavities being doped more than once. The wide range of cavity dopings was done to better understand the feasibility of nitrogen doping for project. For all test RF measurements each cavity was tested at multiple temperatures (Q_0 vs. E_{acc} vs. T) in order to enable decomposition of the RF losses into temperature dependant and temperature independent portions. Initial analysis of RF losses on multiple cavities was presented at IPAC 2015 [1]. These results suggest that there is a correlation between the doping/electropolish parameters and the temperature dependent RF losses, but it is unclear what mechanism would explain this correlation.

Another mystery that arose during the initial phase of development was the occurrence of lower than expected temperature independent losses after a surface reset of 35 to 50 μm.[2] These so-called "re-baselined" cavities had performance similar to standard preparation EP cavities but with the Q_0 vs. E_{acc} @ 2.0 K curve shifted up. This suggested that there was still a substantial amount of nitrogen left in the niobium and that the nitrogen may play more than one role in the niobium.

In this paper we present a new study on two cavities which seeks to explain the correlation between the temperature dependant portion of the surface resistance with doping/EP as well as the higher than expected Q_0 at 2.0 K after surface reset.

CAVITY HISTORY

The two cavities chosen for this study were RDT-13 and TD-5; both cavities are 1.3 GHz TESLA shaped single cell cavities. RDT-13 uses the symmetric long end cell design (geometry factor of 279) made out of fine grain niobium RRR>250 from Tokyo-Denki. The cavity had been doped multiple times before this study, with a 40-45 μm chemistry reset between doping and an 80 μm reset before this study. After its last doping (800°C 3hrs N1A10 EP5), the cavity had a rather strange temperature independent component to its Q_0 vs. E_{acc} performance, similar to a medium field Q_0 slope. At the time this was presumed to be caused by a "bad" EP, and therefore 80 μm was taken off the inner surface to ensure what was thought to be a full surface reset, i.e. no doping left.

TD-5 is symmetric center cell design (geometry factor of 270) cavity made out of large grain niobium RRR>300 from Tokyo-Denki. After manufacturing and before the baseline test, the cavity was post purified at 1250°C with titanium. The full cavity histories after half-cell machining are presented in Table 1.

TEST PLAN

This study was designed to follow two different cavities through a single nitrogen doping followed by multiple EP removals with RF tests. After the first RF test for each EP, each cavity was warmed up to 120 K for a minimum of 5 hours and then re-cooled and tested. Such incremental steps with removal by EP continued until there was a positive slope in the temperature dependant portion of the surface resistance. In addition, after the first EP removal of 5 μm EP, the outsides of the cavities were BCP'ed removing 10 μm and retested. The full test outline is shown in Table 2.

RESULTS

This study was designed to follow two different cavities through a single nitrogen doping followed by multiple EP removals with an RF test after each removal. The RF data is presented in multiple ways; Q_0 vs. E_{acc} at 2.0 K, temperature independent and dependant surface resistance vs field, as well as low field Q_0 vs. T on TD-5.

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Table 1: Cavity History of RDT-13 and TD-5 before Doping Study

RDT-13	TD-5
Half cell BCP (1:1:1) 30 µm	Half cell BCP (1:1:1) 30 µm
Welding	HT 600°C 10 hrs
BCP (1:1:2) 100 µm	Half cell BCP (1:1:1) 30 µm
800°C 3 hrs N2A20 EP 15 µm	Welding
BCP(1:1:2) 40 µm	BCP (1:1:1) 90 µm
800°C 3 hrs N20A10 EP20 µm	600°C 10 hrs
EP 45 µm	BCP(1:1:1) 60 µm
800°C 3 hrs N1A60 EP 20 µm	1250°C/3 hrs Ti box
EP 45 µm	30 µm EP
800°C 3hrs N1A10 EP5	Outside BCP (10 µm)
EP 80 µm	

Table 2: Doping/EP Steps in this Study

Step #	Process
1	800°C 3 hrs N20A0
2	5µm EP + RF test
3	~120K soak + RF test
4	Outside BCP + RF test
5	15µm EP + RF test
6	~120K soak + RF test
7	20µm EP + RF test
8	~120K soak + RF test

2.0 K Q_o vs E_{acc}

The 2.0 K Q_0 vs. E_{acc} data for all dopings/EP for both cavities is shown in Fig 1. In addition, the baseline measurement of TD-5 after an EP but before doping is also shown; there is no baseline data for RDT-13 without doping. Both cavities after the first doping N20A0_EP5 show the characteristic mid-field *Q* rise and early quench with "heavy" doping (RDT-13 quench field on previous tests has been above 35 MV/m). RDT-13 did have a much lower Q_0 than expected, and was MP limited between 14 and 23 MV/m for all tests. After the second EP, both cavities lost their mid-field *Q* rise, but still had higher than normal Q_0. And even after the third EP, the Q_0 still remained higher than expected.

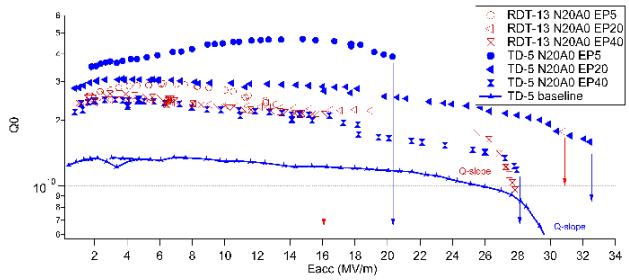

Figure 1: Q_0 vs. E_{acc} for all tests before thermal cycles, including TD-5's non-doped baseline test. Down arrows represent quench fields.

Fitting Results

The 2.0 K Q_0 vs. E_{acc} data alone does not paint a clear picture whether the doping/EP between the two cavities are identical or not. In order to better understand the differences and similarities in the doping/EP between the two cavities, the temperature dependant and independent portions of the effective surface resistance needs to be looked at separately. For each cavity test, the data set was fitted using the simple function:

$$R_{s-eff} = RS_{resid}(B_{pk}) + R_{BCS}(B_{pk}, T) \left[= \frac{A(B_{pk})}{T} e^{-\frac{U}{T}} \right]$$

with U=17.02 representing a fixed gap. The fitting used is outlined in LINAC 2014, IPAC 2015, and LCLS-II high Q_0 2014 report; the fitting protocols are similar to Romanenko, et al. and Dhakal et al.[1-5].

From the surface decomposition fitting, two different plots are extracted, one representing the temperature dependant portion of the surface resistance "*A*" function vs. surface peak magnetic field and another temperature independent portion "*RS*" vs. surface peak magnetic field.

The temperature dependant plots of "*A*" are shown in Figure 2. After decomposition, it is clear that the doping between the two cavities is qualitatively the same, although the y-intercept and higher field portion for the cavities appear slightly different. From the plot is it clear that the portion of the surface resistance that causes the mid-field *Q*-rise is almost gone after the second EP, and is completely gone after the 40 µm EP.

The temperature independent plots of "*RS*" are shown in Figure 3. After decomposition there is no clear correlation between the cavities for each doping. This is not unexpected, because the two cavities were tested in different test setups that have different magnetic fields as well as different cooling rates, which conditions are expected to dominate the *RS*. The steep slope on RDT-13's N20A0EP5 *RS* is under investigation with a different cavity that shows the same results. The high *RS* on RDT-13 N20A0EP20 is strongly correlated with higher than nominal magnetic field and non-standard cooldown which occurred after a system shutdown. This was fixed before the cooldown of RDT-13 N20A0EP40.

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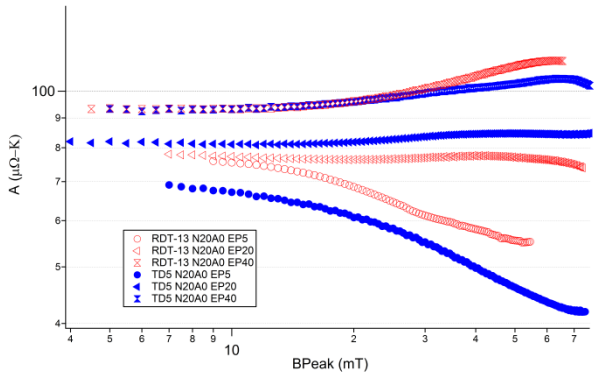

Figure 2: Temperature dependant "*A*" fitting parameter vs. field for all three dopings for both RDT-13 and TD-5, data taken before 120 K soak, data admin limited to 75 mT or first quench.

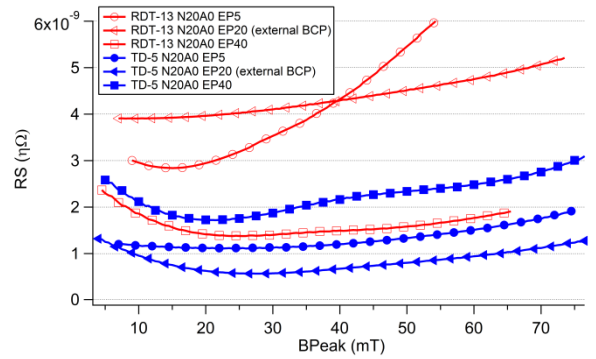

Figure 3: Temperature independent "*RS*" fitting parameter vs. field for all three dopings for both RDT-13 and TD-5, data taken before 120 K soak, data admin limited to 75 mT or first quench.

In all cases, the temperature dependence of surface resistance is measured at B_p~8 mT of peak rf field, and material parameters such as the energy gap, electronic mean free path and residual resistance were extracted using the Halbritter BCS theory code as shown in Fig. 4. The extracted parameters along with the breakdown field and the quality factor just before the breakdown field are summarized in Table 3.

Table 3: Material Parameters Extracted for Cavity TD-5 from the Fits of *Q(T)* Curves Using the BCS Theory after the Several Subsequent Material Removal Steps by EP

Removal by EP	Δ/k_BT_c	mfp (nm)	R_{res} (nΩ)
Baseline 30 μm	1.77±0.01	220±48	6.5±0.4
5	1.86±0.02	29±15	0.8±0.1
20	1.85±0.01	26±9	1.7±0.1
40	1.84±0.01	160±31	1.2±0.1

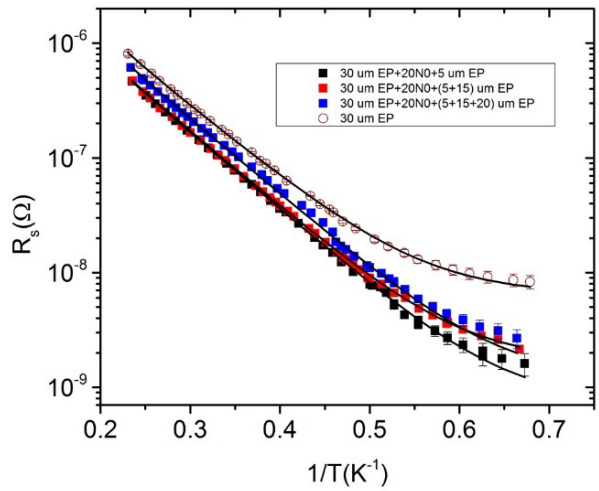

Figure 4: Surface resistance data from TD-5 taken at ~8 mT. Data and fit of R_s vs $1/T$ using the BCS theory as described in text to extract the superconducting parameters. Fitting is using the Halbritter code.

120K Soak Data

For all 6 cavity tests, only one test showed any sign of a change in the Q_0 vs. E_{acc} after the 120 K soak. This happened on RDT-13 N20A0 EP40 where there was a small change in the slope of the residual resistance. It is unclear if the data is showing a trend that would be enhanced with more EP or not, but we present the fitting of the temperature dependant "*A*" and temperature independent "*RS*", showing a change in *RS* which becomes large with field, Fig 5.

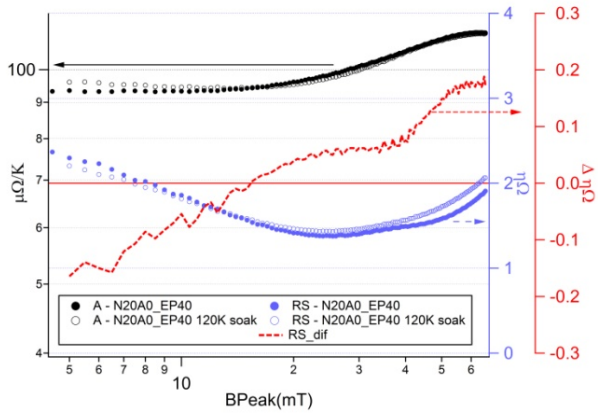

Figure 5: *RS*, *A*, and differences in *RS* before and after 120 K soak for 5 hour (10 hours above 90 K) on RDT-13 N20A0_EP40.

External BCP

After the 5 μm EP, both cavities received a 10 μm external BCP. Unfortunately for RDT-13, its test was FE loaded and the cavity had to move forward for an additional EP before a retest could be performed. But from the residual resistance observed between the 5 μm EP and 20 μm EP, the character of the residual changed from being more or less flat after the BCP and sloped

before the BCP. This effect from an external BCP after multiple dopings will be investigated in the future. In addition, in TD-5 a strange *Q*-switch appeared in the range 15-20 mT which spoiled the data, so the large grain data will also be re-investigated in the future.

SIMS Measurements

In parallel to the cavity testing, SIMS measurement looking at the nitrogen content on like-treated witness samples (doping in same furnace run, but EP'd separately with the same parameters) was also performed. These results are outlined in Figure 6. The data show that there is not difference in the nitrogen at the surface between the 5 and 20 µm EP and 40% of the nitrogen still remained after the 40 µm EP. The detailed analysis of the samples will be published elsewhere.

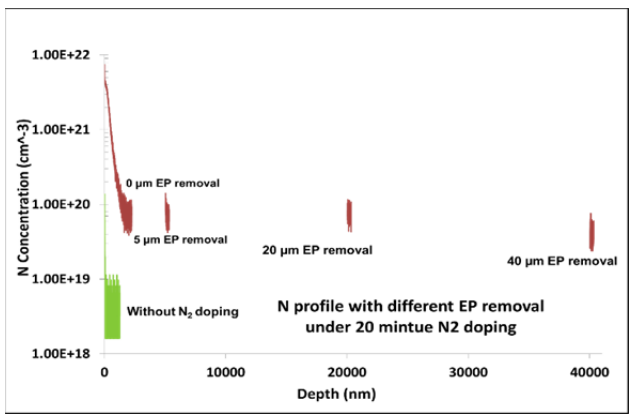

Figure 6: Nitrogen content at the surface of witness samples treated in the same furnace run as RDT-13 and TD-5. EP performed with the same paramters, but in differnet setup.

COMMENTS

- There is a clear correlation in the temperature dependant parameter "*A*" between dopings on both cavities.
- The "*A*" parameter signature of the medium field *Q*-rise is gone in both cavities after 20 µm total EP, yet the nitrogen content at the surface is identical within the measurement errors of the SIMS data.
- After 40 µm of EP there is ~ 40% of the nitrogen concentration remaining from SIMS data, suggesting the remaining nitrogen is a possible cause for the higher than expected Q_0 in TD-5 compared to the baseline.
- RDT-13's higher than expected "*RS*" in the 5 µm and 20 µm EP is under investigation but is correlated with a higher than expected remnant field and non-standard cooling because of a system shutdown.

ACKNOWLEDGMENT

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