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NEW INSIGHTS INTO HEAT TREATMENT OF SRF CAVITIES IN A LOW-PRESSURE NITROGEN ATMOSPHERE*

Dan Gonnella, Matthias Liepe, CLASSE, Cornell University, Ithaca, NY, United States

Abstract

Recent results from Cornell and FNAL have shown that superconducting RF cavities given a heat treatment in a nitrogen atmosphere of a few mTorr display an increase in Q_0 with increasing accelerating field, opposite to the medium field Q slope usually observed. Three cavities was prepared at Cornell using this method and subsequently tested after different amounts of material removal. Cavity performance and material properties were extracted for each cavity and correlated with material removal. This has given new insights into how material properties and the anti-Q slope depend on cavity preparation.

INTRODUCTION

New light sources such as the SLAC Linear Coherent Light Source II (LCLS-II) require many SRF cavities in CW operation. In order for the economic viability of these machines to be achieved, a high quality factor must be reached in all of the cavities to minimize power dissipation and wall power costs. Until recently, the state of the art in cavity performance was an intrinsic quality factor, Q_0, of $2{\times}10^{10}$ at 2.0 K and 16 MV/m (a medium field usually required for light sources) using standard ILC treatment and HF rinsing [1]. LCLS-II however, requires a Q_0 of 2.7×10^{10} at 2.0 K and 16 MV/m. In order to achieve this jump in quality factor performance, the use of "nitrogen-doped" cavities has been proposed. These cavities were first explored at FNAL [2] and later at Cornell [3] and shown to have an increasing Q in the medium field region, opposite of what is usually seen in SRF cavities. While having great Q's, these cavities are susceptible to a lower quench than standard cavities (20 MV/m). As part of the LCLS-II High Q program at Cornell, 5 single-cell cavities have been fabricated and given a nitrogen doping. Three of these cavities have been tested and the performance will be reported on here as well as the material properties extracted which provide insight into the high Q's that these cavities display.

CAVITY PREPARATION AND TESTING

Five single-cell 1.3 GHz ILC cavities were fabricated from RRR 300 niobium at Cornell. Three of these cavities have been tested so far, and we will limit our discussion to them. Each received 100 μm vertical electropolishing followed by an 800°C heat treatment in vacuum for 4 days. After the vacuum heat treatment, nitrogen was injected into the furnace for 20 minutes. The nitrogen was injected up to a pressure of 38 mTorr and allowed to decay. Once it had decreased to 30 mTorr, more was injected, resulting in a final pressure of 57 mTorr which decayed until the end of the 20 minutes. Following the nitrogen treatment, the furnace was pumped back to vacuum and the cavities continued to bake in vacuum for an additional 30 minutes. A profile of the nitrogen pressure as a function of time is shown in Fig. 1. It was found that the nitrogen intake per cavity was 48 Torr-Liters. After heat treatment, the cavities were given different amount of VEP: 18, 5, and 12 μm equator removal respectively. Finally the cavities were each tested in Cornell's vertical test dewars. During these tests the following were measured: quality factor vs temperature at 5 MV/m, quality factor vs accelerating field at various temperatures, and resonance frequency vs temperature. From resonance frequency vs temperature and quality factor vs temperature, SRIMP could be used to fit the data and extract T_c, mean free path, energy gap ($\Delta/k_B T_c$), and residual resistance [4].

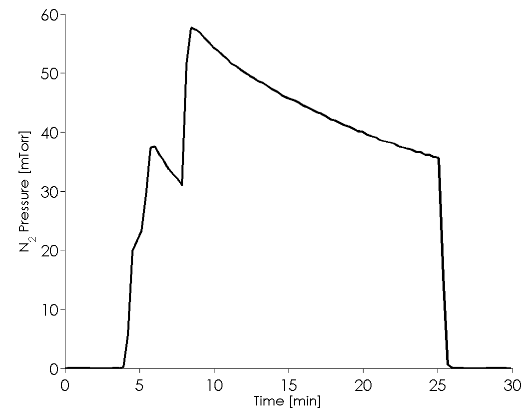

Figure 1: A profile of the nitrogen pressure during the doping phase as a function of time.

QUALITY FACTOR PERFORMANCE

2.0 K performance of the three cavities is shown in Fig. 2. Also shown is the LCLS-II Q specification. It can be seen that each of these cavities meets specifications with Q_0 on the order of 4×10^{10} at 16 MV/m. We can see that the third cavity which received 12 μm of material removal after bake had the best performance with a Q_0 of $4.5{\times}10^{10}$ at operating gradient. Additionally, this cavity quenched much higher than the other two cavities, reaching 32 MV/m, the highest field reached in a nitrogen-doped cavity. The performance of this cavity at various temperatures is shown in Fig. 3. We can see that the cavity has a very low residual resistance, reaching Q's of more than 1×10^{11}.

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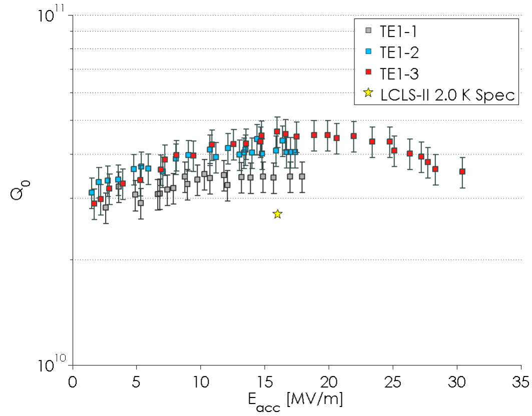

Figure 2: 2.0 K Q_0 vs E_{acc} performance for the three cavities.

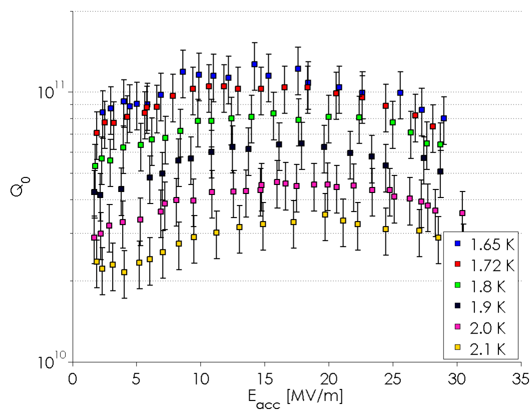

Figure 3: Q_0 vs E_{acc} at different temperatures for TE1-3.

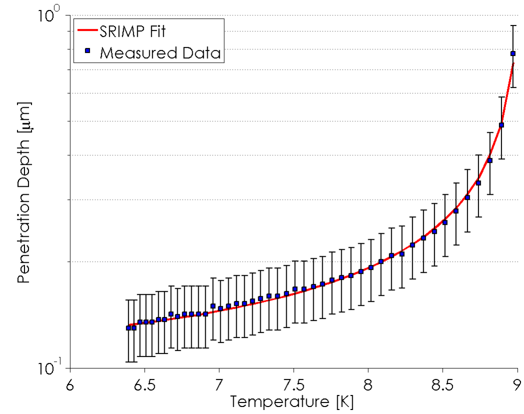

Figure 4: An example SRIMP fit for penetration depth vs temperature for TE1-2.

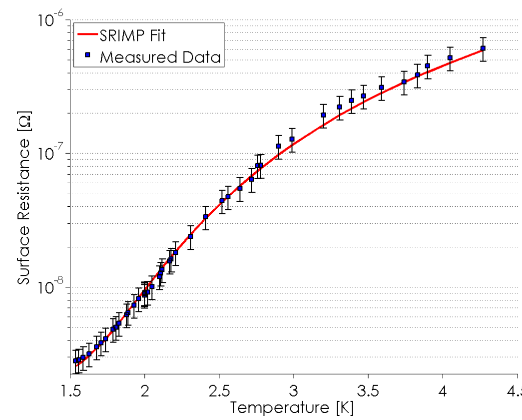

Figure 5: An example SRIMP fit for surface resistance vs temperature for TE1-2.

MATERIAL PROPERTIES

Material properties were extracted from resonance frequency vs temperature and Q vs temperature. T_c and mean free path were extracted from penetration depth vs T (obtained from resonance frequency vs temperature) and energy gap and residual resistance were extracted from Q vs T. An example of the penetration depth fit is shown in Fig. 4 and the Q vs T fit (converted to surface resistance vs T) in Fig. 5. A summary of these material properties is shown in table 1. Also shown is the Ginzburg-Landau constant κ_{GL} and the lower critical field B_{c1} which are calculated from the extracted mean free path. For each cavity, the residual resistance is very low, on the order of 2 nΩ and $\Delta/k_b T_c$ is a bit higher than for typical niobium (typical niobium is 1.85). The mean free path for each cavity is very small, as small as 8 nm for TE1-2. This suggests that the RF layer is very dirty and even dirtier than 120°C baked cavities which have a mean free path of ~30 nm. Interestingly, TE1-3, the best performing cavity, had the largest mean free path with $\ell = 12$ nm. The overall low BCS surface resistance of the N-doped cavities is caused by lowering the mean free path near its optimal value by adding nitrogen as impurity. Nitrogen impurities do not lower the critical temperature of niobium, unlike oxygen [5].

FIELD DEPENDENCE OF THE SURFACE RESISTANCE

The surface resistance can be broken into a temperature dependent BCS resistance (R_{BCS}) and a temperature-independent residual resistance (R_{res}) [6]. These can be extracted as a function of field using SRIMP to fit the measured temperature dependence of the surface resistance at a given field. R_{BCS} at 2.0 K is shown in Fig. 6 for each of the cavities. It can be clearly seen that in the anti-Q slope region a decreasing BCS resistance is present (from ~7 to ~4 nΩ). The residual resistance is shown in Fig. 7. Because the residual resistance is mostly constant in the anti-Q slope region and the BCS resistance is decreasing, we claim that the anti-Q slope is a result of the BCS resistance decreasing with increasing field.

It is of interest to discuss the field dependence of the BCS surface resistance as a function of the logarithm of the peak surface magnetic field [7]. The theory presented in ref [7].

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Table 1: Summary of Extracted Material Properties

Property	TE1-1	TE1-2	TE1-3
Equator VEP [μm]	18	5	12
T_c [K]	9.2 ± 0.9	9.1 ± 0.9	9.2 ± 0.9
$\Delta/k_B T_c$	1.94 ± 0.02	1.99 ± 0.02	1.95 ± 0.02
Mean Free Path [nm]	8 ± 2	6 ± 2	12 ± 3
R_{res} [nΩ]	2.5 ± 0.5	2.0 ± 0.4	1.4 ± 0.3
κ_{GL}	8 ± 1	10 ± 2	6 ± 1
B_{c1} [mT]	44 ± 14	38 ± 15	53 ± 13
Quench Field [MV/m]	20	18	32

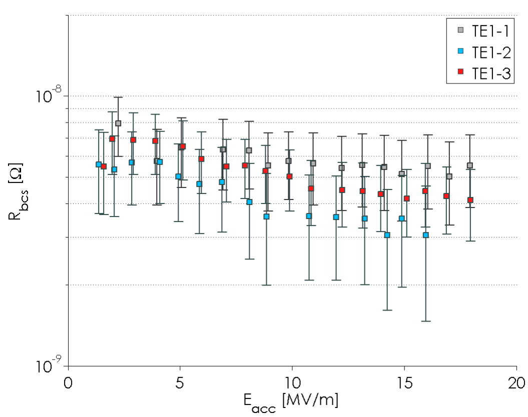

Figure 6: The 2.0 K BCS resistance vs E_{acc} for the three cavities.

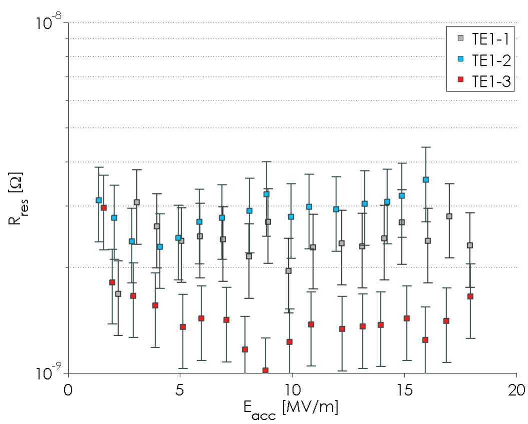

Figure 7: The residual resistance vs E_{acc} for the three cavities.

predicts that a smearing of the density of state by the rf field can lead to a logarithmic dependence of R_{BCS} with field amplitude. If we look at the change in BCS surface resistance, $\Delta R_{BCS} = R_{BCS}(B_{pk}) - R_{BCS}^{max}$, with R_{BCS}^{max} being the maximum BCS resistance, we can see that in the region of 15 mT $\leq B_{pk} \leq$ 70 mT the BCS resistance indeed decreases with the logarithm of the field. Fig. 8 shows an example of this for TE1-3 at 2.1 and 2.0 K.

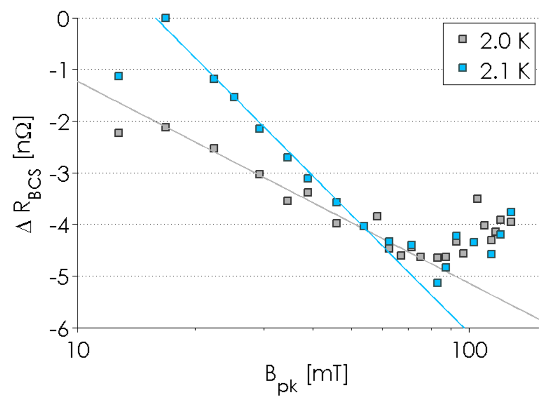

Figure 8: ΔR_{BCS} vs B_{pk} for TE1-3. In the medium field region, the BCS resistance decreases linearly with the logarithm of the peak surface magnetic field.

CONCLUSION

Nitrogen doping of the RF surface layer of niobium SRF cavities has been shown to have a positive impact on the Q performance of SRF cavities. They display overall high quality factors with an anti-Q slope in the medium field region. Three single-cells fabricated at Cornell were given a nitrogen doping and different amounts of material removal. This resulted in quality factors higher than 4×10^{10} at 16 MV/m and 2.0 K. Additionally, one cavity reached 32 MV/m, well above the 16 MV/m LCLS-II operating point, providing encouragement for the use of these cavities at fields above 16 MV/m. Nitrogen doping leads to dirty superconducting surface layer, with mean free paths on the order of 10 nm. This allows for an optimum dirtiness to be achieved that lowers the BCS resistance and contributes to the anti-Q slope. It was also found that the BCS resistance decreases linearly with the logarithm of the peak surface magnetic field in the medium field (anti-Q slope) region. This decreasing BCS resistance is the cause of the anti-Q slope observed in nitrogen-doped cavities.

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