NITROGEN TREATED CAVITY TESTING AT CORNELL*

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Abstract

Recent results from Cornell, FNAL, and TJNAF have shown that superconducting RF cavities given a heat treatment in a nitrogen atmosphere show higher Q_0 at operating gradients at 2.0 K than standard SRF cavities. Here we present on recent results at Cornell in which five single cell cavities and three 9-cell cavities were tested after receiving various nitrogen-doping treatments. Cavity performance was correlated with treatment, and samples treated with the cavities were analyzed with SIMS. These results provide new insights into the science behind the excellent performance that is observed in these cavities.

INTRODUCTION

New light sources such as LCLS-II at SLAC require CW SRF cavity operation. In order to operate the machine in this mode, high intrinsic quality factor (Q_0) must be achieved in the medium field region. The LCLS-II specification is a Q_0 of 2.7×10^{10} at 16 MV/m and 2.0 K [1]. Until recently, this goal was very ambitious, however with the introduction of nitrogen doping, quality factors on this order and above can now be repeatedly achieved. Nitrogen doping consists of heat treating SRF cavities in a low pressure nitrogen atmosphere resulting in some nitrogen diffusion into the niobium. It has been shown that this process has the ability to completely remove the medium field Q slope usually seen in SRF cavities and even causes an anti-Q slope where the Q will increase between ~ 5 and ~ 20 MV/m [2, 3]. An effort is currently underway at Cornell, FNAL, and TJNAF to study the effect of nitrogen doping on single and 9 cell cavities for LCLS-II [4]. In this paper we discuss the current progress on this subject at Cornell.

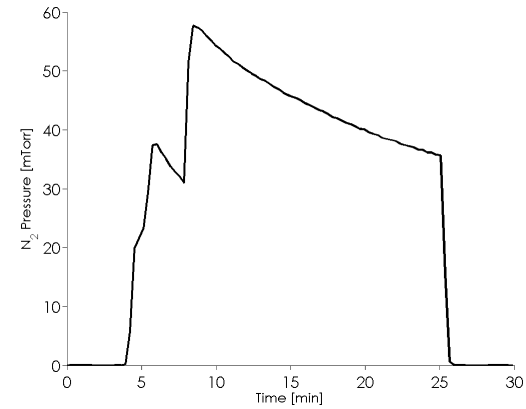

Figure 1: The nitrogen pressure profile during the heat treatment of TE1-1, 2, and 3.

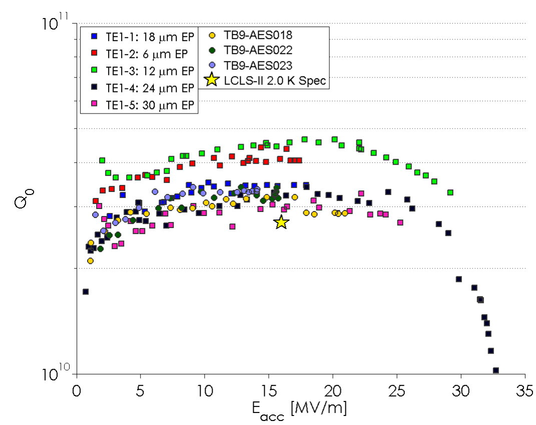

Figure 2: Q_0 vs E_{acc} performance and 2.0 K for all eight cavities. Errors are 20% on Q_0 and 10% on E_{acc}

CAVITY TREATMENT AND TESTING

Five single-cell 1.3 GHz ILC shaped cavities (constructed at Cornell) and 3 ILC 9 cell cavities were given the same doping treatment. This consisted of a bulk VEP (~ 100 µm), followed by a de-gas in UHV furnace at 800°C in vacuum, followed by 20 minutes in a nitrogen atmosphere (pressure profile shown in Fig. 1), followed by an additional 30 minutes in vacuum. After doping, a nitride layer forms on the surface (this will be clear from SIMS data which will be discussed in a later section). This nitride layer must be removed before testing. Each cavity was given a final VEP to remove this nitride layer and to change the doping level of the RF surface layer. The five single-cells were given different amounts of material removal in order to study how the cavity performance evolves with material removal. The 9 cells were given final EP in order to achieve the best performance. The removal amounts are summarized in Table 1.

For each cavity, the following was measured: Q_0 vs temperature, resonance frequency vs temperature (during warm-up), and Q_0 vs E_{acc} at 1.6, 1.7, 1.8, 1.9, 2.0, and 2.1 K. This extensive Q_0 vs E_{acc} data was used to extract the residual (temperature independent) and BCS (temperature dependent) resistances and their field dependence.

CAVITY PERFORMANCE

The 2.0 K Q_0 vs E_{acc} performance for each of the eight cavities is shown in Fig. 2. The LCLS-II 2.0 K specification of 2.7×10^{10} at 16 MV/m is also shown.

We can see from Fig. 2 that all the single-cell cavities easily meet the LCLS-II spec. Cavities 1 and 2 are the only single-cells to quench below 20 MV/m (a phenomenon seen in many other nitrogen-doped cavities [2, 3, 5]). The

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Table 1: Summary of Cavity Parameters

Cavity	# of Cells	Final EP [μm]	Max Q_0 at 2.0 K ($\times 10^{10}$)	Quench Field [MV/m]	R_{res} [nΩ]
TE1-1	1	18	3.5	18	2.5 ± 0.5
TE1-2	1	6	4	16	2.0 ± 0.4
TE1-3	1	12	4.5	33	1.4 ± 0.3
TE1-4	1	24	3.5	34	1.8 ± 0.4
TE1-5	1	30	3	26	1.3 ± 0.3
TB9-AES018	9	24	3	22	2.3 ± 0.4
TB9-AES022	9	14	3.4	16	4.4 ± 0.8
TB9-AES023	9	17	3.5	14	3.0 ± 0.6
Mean Values			3.6	22	2.5

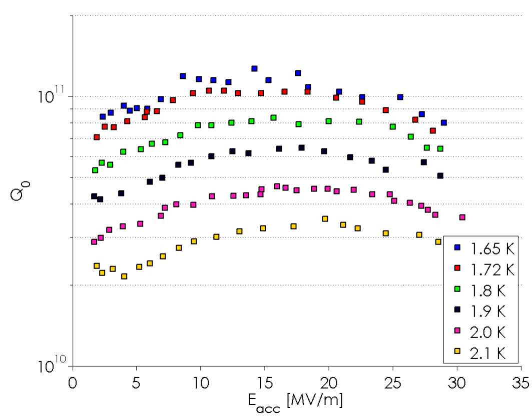

Figure 3: Q_0 vs E_{acc} performance of TE1-3 at all measured temperatures below the lambda point.

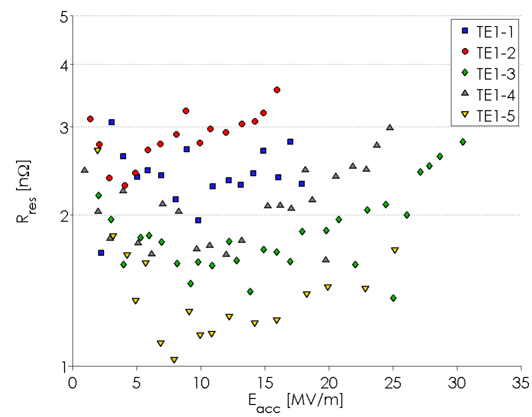

Figure 4: R_{res} vs E_{acc} for the five single-cell cavities. Uncertainties are ~ 1 nΩ.

other three single-cells however reach much higher fields, with TE1-4 reaching 34 MV/m. More importantly, the Q_0 remains high for these cavities up to more than 25 MV/m. Clearly visible for each single-cell is a strong anti-Q slope. Figure 3 shows the Q_0 vs E_{acc} performance of TE1-3 at all temperatures measured below the lambda point. We can see that at 1.8 K the Q_0 is already more than 8×10^{10} and at 1.6 K it reaches higher than 1×10^{11}.

The 9-cell performance is also promising. TB9-AES018 and TB9-AES022 easily passed LCLS-II spec with a Q_0 more than 3×10^{10}. TB9-AES018 reached a field of more than 22 MV/m while TB9-AES022 reached 16 MV/m. TB9-AES023 had high Q and no field emission but quenched at 14 MV/m for unknown reasons. Cavity performance for both single and 9-cell cavities is summarized in Table 1. All three 9-cell cavities meet LCLS-II Q_0 specification. Only one is limited to fields less than 16 MV/m, but average quench field of all 9-cells is above the 16 MV/m specification.

FIELD DEPENDENCE OF THE SURFACE RESISTANCE

The Q_0 vs temperature data was used with SRIMP [6] to extract the residual resistance for each cavity. These values are summarized in Table 1. The extensive Q_0 vs E_{acc} data at different temperatures was also used to extract the field dependent residual and BCS resistances for each single-cell cavity. The residual resistance as a function of accelerating field is shown in Fig. 4. The residual resistance decreases between 0 and 6 MV/m due to low field Q slope and increases above 25 MV/m due to high field Q slope. However, in the anti-Q slope region (5-20 MV/m) it remains constant within measurement uncertainties.

A field dependent BCS resistance has been shown to cause the anti-Q slope observed in nitrogen-doped cavities [3]. Figure 5 shows ΔR_{BCS} (the change in BCS resistance) as a function of peak magnetic field (plotted on a log scale) for all five single-cell cavities. We can see that between 20 and 70 mT, the BCS resistance decreases with the logarithm of the field. This behavior is similar to cavities heat treated at very high temperatures [7]. This logarithmic dependence is predicted by theory presented in [7], which discusses smearing of the density of states by the RF field.

SAMPLE ANALYSIS

A niobium sample treated with TE1-4 and TE1-5 was analyzed using SIMS. The nitrogen concentration was measured in fine steps between 0 and 7 μm and in 5 μm steps between 18 and 100 μm. These results are shown in Fig. 6. Additionally, the five single-cells are included for reference. We can see that the nitride layer is present up to about 2 μm into the niobium. Below the nitride layer, the nitrogen concentration slightly increases for a few microns and then decreases. It is important to note that the concentration of nitrogen

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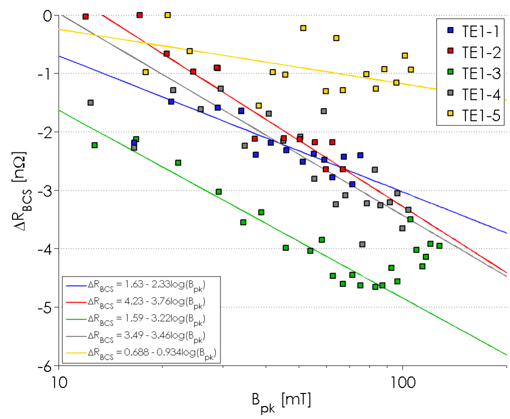

Figure 5: ΔR_{BCS} vs B_{pk} for all five single-cell cavities. The BCS resistance decreases with the logarithm of the field between 20 and 70 mT.

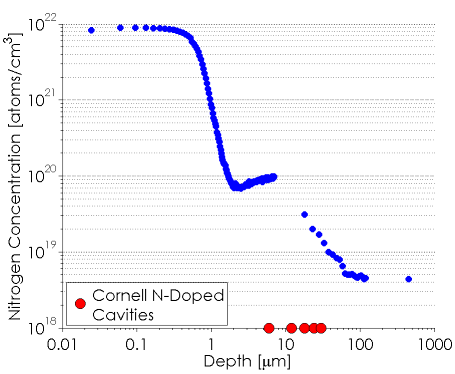

Figure 6: SIMS results from a sample treated with TE1-4 and TE1-5. Single-cell cavities are also included for reference.

doesn't reach the background level until about 50 µm into the surface. This analysis shows that the doping layer is ~30 to 50 µm thick from the 20 minute 800°C nitrogen treatment plus 30 minutes in vacuum. This gives a final EP range of 5-30 µm with the same doping level, and thus the same Q_0 performance. This wide range makes the performance insensitive to the value of final EP removal, and allows for re-etching if needed (for example to remove field emission or defects). In this doping range, the doping level is $\sim 5 \times 10^{19}$ atoms/cm^3. From this one can estimate the mean free path as ~80 nm. This is in good agreement with mean free path extracted from RF data [8].

CONCLUSIONS

Five single-cell cavities and three 9-cell cavities have been successfully nitrogen-doped and tested at Cornell. All five single-cells and three 9-cells easily met the LCLS-II Q specification of 2.7×10^{10} at 16 MV/m and 2.0 K. Three of the single-cells and one 9-cell reached much higher fields than required by LCLS-II, with TE1-4 reaching 34 MV/m. Each cavity showed the anti-Q slope usually seen in nitrogen-doped cavities which was attributed to a decreasing BCS resistance which decreased with the logarithm of the peak magnetic field in the anti-Q slope region. Sample studies with SIMS suggest that the Cornell nitrogen-doping recipe results in nitrogen being present up to at least 50 µm into the niobium.

These measurements have demonstrated the repeatability of the Cornell recipe to achieve high Q in single and 9-cell cavities with nitrogen-doping. Additionally, the recipe is robust and produces good Q results for a wide range of material removal. This is very important for production because it allows the removal of additional material without loss of performance if a cavity is plagued by field emission. For the first timem a nitrogen-doped cavity has also been tested in cryomodule for the first time [9]. It has also been shown that nitrogen-doped cavities are more susceptible to losses from magnetic field than other cavities [10]. Overall, these results are a very important step towards a CW light source such as LCLS-II with a high Q requirement in the medium field.

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