IMPROVED N-DOPING PROTOCOLS FOR SRF CAVITIES*

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Abstract

Nitrogen-doping has been shown to consistently produce better quality factors in SRF cavities than is achievable with standard preparation techniques. Unfortunately, nitrogen-doping typically brings with it lower quench fields and higher sensitivities of residual resistance to trapped magnetic flux. Here we present work to understand these effects in hopes of mitigating them while maintaining the high Q desired by future projects. Using a nitrogen diffusion simulation, material parameters of nitrogen-doped cavities can be predicted prior to doping. These simulations results are consistent with SIMS data taken from samples treated with cavities. The nature of doping's effect on quench field has also been studied using CW and pulsed measurements. These results have allowed us to better understand the nature of nitrogen-doping and its effect on cavity performance.

INTRODUCTION

As accelerators continue to push the frontiers of modern technology, increasing the cryogenic efficiency of the SRF cavities used for acceleration is necessary to maintain economic viability. Nitrogen-doping has been shown to improve the intrinsic quality factor, Q_0, of SRF cavities compared with standard preparation techniques [1]. Nitrogen-doping allows cavities to reach Q_0's as high as 5×10^{10} at 16 MV/m, however it comes with several challenges. The doping itself leads to a reduction in mean free path of the material, which in turn lowers the critical fields. Nitrogen-doped cavities are typically plagued with low quench fields, limiting their ability to be used in high gradient applications. Here we discuss the results of sample analysis and the development of a nitrogen diffusion simulation to guide the accelerator physicist's hand when choosing a recipe and summarize studies of how nitrogen-doping affects the quench fields of cavities.

NITROGEN-DOPED CAVITIES PREPARED AND TESTED

Cornell has completed testing of fifteen nitrogen-doped cavities: ten single-cells and five 9-cell cavities. These cavities were given differing levels of nitrogen-doping to study the effects of varying doping levels on cavity performance and quench fields. Nitrogen-doping typically consists of a heat treatment at high temperatures (700-1000°C) for some minutes in a few mTorr of N_2 gas followed by a further heat treatment in vacuum (known as an anneal). For each of the single-cells, material parameters such as the mean free path were extracted using BCS fitting [2, 3].

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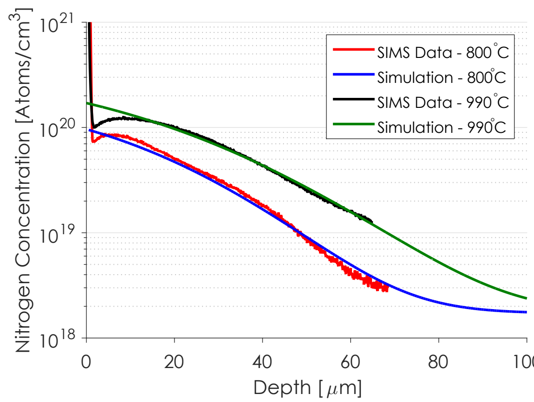

Figure 1: Comparison of nitrogen diffusion simulation for nitrogen concentration with results from SIMS measurements for two dopings.

NITROGEN DIFFUSION SIMULATION AND SIMS RESULTS

The diffusion process of nitrogen into niobium is well understood and can be modeled [4]. During the diffusion process, a nitride layer forms on the surface of the niobium. Unfortunately, this nitride is quite lossy in RF fields and must be removed prior to cavity testing. Below the nitride, nitrogen concentration is significantly higher than background levels in clean niobium. The methods described in [4] were used to develop a model which can predict nitrogen concentration as a function of depth into niobium for a given set of doping parameters.

As a check on the diffusion simulation, two samples were prepared with nitrogen-doping in the Cornell UHV furnace. Both samples were analyzed with Secondary Ion Mass Spectroscopy (SIMS) which measures the concentration of nitrogen as a function of depth into the material. The first sample was given a doping at 800°C for 20 minutes followed by a 30 minute anneal. The second was given a doping at 990°C for 5 minutes. The results of the SIMS measurements on these samples and a comparison with the prediction from the diffusion simulation is shown in Fig. 1. It is clear that there is very good agreement between the simulation and SIMS data for both dopings. This demonstrates the accuracy of the diffusion simulation and allows one to make predictions on the nitrogen-doping level before carrying out a doping.

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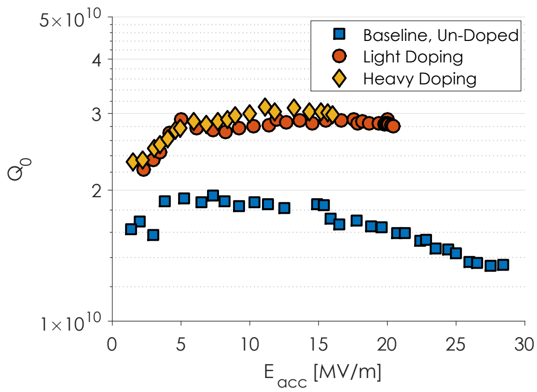

Figure 2: Q_0 versus E_{acc} for AES030 (9-cell cavity tested at Cornell) at 2.0 K. Cavity quenched at ~30 MV/m prior to nitrogen-doping. After a heavy doping the quench field was reduced to ~15 MV/m. Following a reset and a light doping, the quench field was reduced to ~20 MV/m.

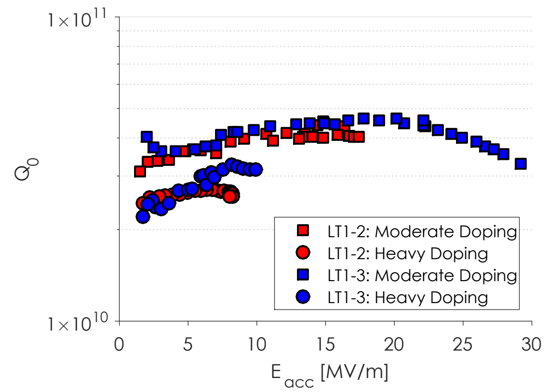

Figure 3: Q_0 versus E_{acc} for LT1-2 and LT1-3 (single-cell cavities) at 2.0 K. Stronger doping resulted in lower quench fields of the same cavities.

CHANGE IN QUENCH FIELD FROM DOPING

Nitrogen-doping is typically associated with a reduction in the quench fields of SRF cavities. The mechanism behind this effect, however, was not well understood. In order to further probe this effect, a 9-cell cavity was tested with three different preparations: a standard ILC treatment, a light nitrogen-doping[1], and a heavy nitrogen-doping[2]. The Q_0 versus E_{acc} performance for all of these preparations at 2.0 K is given in Fig. 2. Without doping the cavity reaches a quench field of ~29 MV/m. After a light doping, the quench field dropped to ~20 MV/m. After the heavy doping, it dropped further to ~16 MV/m. This is suggestive of the amount of doping affecting quench fields: heavier doping gives lower quench fields.

Additionally, two of the single-cell cavities were given moderate and heavy dopings and their performance compared. The Q_0 versus E_{acc} results at 2.0 K for these cavities are shown in Fig. 3. For the moderate dopings, both cavities were doped at 800°C for 20 minutes followed by a 30 minute anneal. LT1-2 was then given 6 μm of VEP and LT1-3 12 μm. For the heavy dopings, LT1-2 was doped at 900°C for 20 minutes followed by a 30 minute anneal and 18 μm of VEP. LT1-3 was doped at 990°C for 5 minutes followed by 5 μm of VEP. It is clear from Fig. 3 that both cavities saw a reduction in their quench fields between moderate and heavy doping. Again, this is indicative of heavier doping leading to a lowering of the quench field.

B_{c1} REDUCTION FROM DOPING

Because of the increased nitrogen concentration present in nitrogen-doped cavities, the mean free path of the RF penetration layer will be severely affected. Lower mean free path will directly lead to a lowering of the lower critical field,

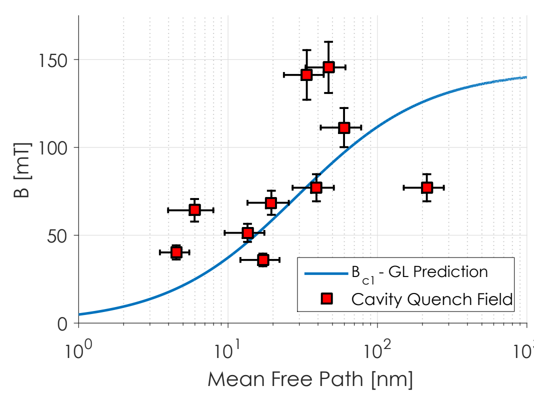

Figure 4: Calculated lower critical field, B_{c1}, from BCS theory compared with the quench fields of the nitrogen-doped single-cell cavities prepared and tested at Cornell.

B_{c1}, and the superheating field, B_{sh}. The change in B_{c1} as a function of mean free path can be calculated from Ginzburg-Landau theory [2]. Figure 4 shows how B_{c1} changes with mean free path. As the mean free path is decreased, B_{c1} also will decrease. Also shown in Fig. 4 are the quench fields for the single-cell nitrogen-doped cavities tested at Cornell. All but two of the ten cavities tested quenched at or above B_{c1}. Of these eight, five quenched very close to B_{c1}. It is likely that quench in these cavities was caused by early vortex penetration at a defect above B_{c1}. For the cavities that reached significantly higher fields than B_{c1}, it is reasonable to assume that they were nearly defect free and/or had defects small enough that vortex entry did not occur until significantly higher fields. Also note that there is a general trend of stronger doping (smaller ℓ) leading to lower average quench fields. The lowering of quench fields that is typically observed in nitrogen-doped cavities is a result of a lowering of B_{c1} caused by lowering of the mean free path.

[1] 800°C for 6 minutes, 6 minute anneal, 14 μm VEP
[2] 800°C for 20 minutes, 30 minute anneal, 26 μm VEP

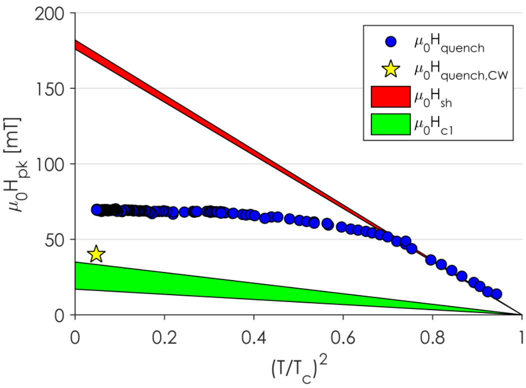

Figure 5: B_{pk} versus $(T/T_c)^2$ for LT1-3, nitrogen-doped at 990°C. At high temperature the quench field follows the superheating field but deviates at lower temperatures, indicative of a quench at a defect.

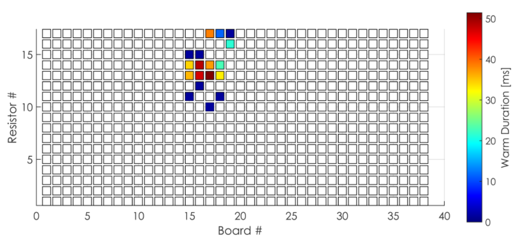

Figure 6: Quench location in LT1-3. The quench was confined to a single location, most likely the site of a defect.

NATURE OF LOW-FIELD QUENCH

In order to further study the nature of the low field quench in nitrogen-doped cavities, the two heavily doped single-cell cavities discussed above (LT1-2 and LT1-3) were tested with Cornell's 1.5 MW klystron. The results from LT1-2 and the experimental methods were presented in [5]. High power pulses were used to find the quench field of the two cavities in short pulse operation as a function of temperature. B_{pk} versus $(T/T_c)^2$ is given in Fig. 5 for LT1-3. Also shown are the calculated critical fields B_{c1} and B_{sh} from GL theory and the CW quench field. At high temperatures, the quench field follows the superheating field. However, as the temperature is lowered, the quench field levels off to a value significantly lower than B_{sh}. This behavior is indicative of a quench at a defect where vortex penetration occurs below B_{sh} but above B_{c1} due to the defect making it more energetically favorable for vortices to enter.

Cavity LT1-3 was then tested to find the quench location and see if it indeed was centered at a defect. Using the Cornell single-cell temperature mapping system, the quench location can be found [6]. Figure 6 shows the results of this measurement. For reference, resistor 9 is centered at the equator. The quench was centered at a single-location just off from the equator. This location was inspected optically but no defect was visible.

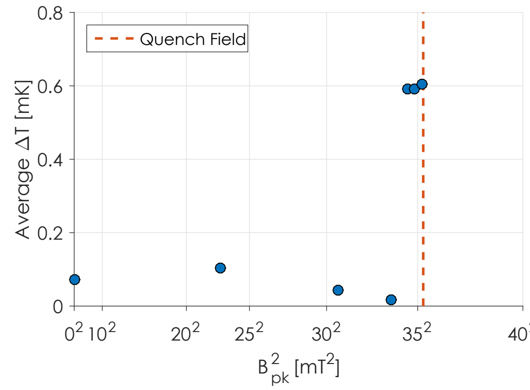

Figure 7: Heating at the quench location of a single-cell nitrogen-doped cavity as measured with temperature mapping. No heating was observed until just prior to the quench field suggesting the quench was caused by flux entry.

LT1-2 was also tested using temperature mapping and the pre-quench heating at the quench location was studied. Figure 7 shows the average heating at the quench location versus B^2_{pk}. No heating was observed until just below the quench field. This behavior is indicative of flux entry at the quench location due to the energy barrier to flux entry dropping to zero.

CONCLUSIONS

The results presented here represent significant progress towards understanding the physics of nitrogen-doped cavities. A diffusion simulation was developed which can accurately predict nitrogen concentration as a function of depth for given doping parameters. This simulation and measurements on samples with SIMS shows that the mean free path of the niobium is significantly altered by nitrogen-doping. This lowering of the mean free path will directly lead to a lowering of the lower critical field, B_{c1}. Indeed, most nitrogen-doped cavities tested at Cornell quench at or just above B_{c1} with heavier doping generally leading to lower quench fields, suggesting that their quenches are due to vortex entry at a defect. This prediction was confirmed on two cavities tested with pulsed measurements and quench detection equipment.

Nitrogen-doping provides significant improvements over more standard cavity preparation techniques. With these benefits however comes lower quench fields due to a lowering of the critical fields. This behavior however can be mitigated through the use of lighter doping recipes. These results suggest that cavities with mean free paths of $30-50$ nm should be prepared in order to maximize Q_0 while minimizing the effects of lower quench fields due to reduction in B_{c1} and B_{sh}.

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