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UNDERSTANDING AND PUSHING THE LIMITS OF NITROGEN DOPING*

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Abstract

This work will describe Fermilab experiments that focus on the optimization of doping parameters to achieve low sensitivity to trapped magnetic flux while maintaining very high Q characteristic of nitrogen doped cavities and same or higher quench fields. Working partially in the context of LCLS-II higher energy upgrade, new doping recipes are pursued and have been found to vary the mean free path of the resonator which is related to the sensitivity to trapped magnetic flux. Moreover, a correlation has been found between lighter doping and higher quench fields while maintaining sufficiently low surface resistance.

INTRODUCTION

Nitrogen doping is a surface treatment for niobium superconducting radio-frequency (SRF) cavities capable of producing ultra-high quality factors and very low BCS surface resistance, thereby decreasing the cryogenic load and ultimately driving the cost of machines down [1-3]. However, cavities subject to this surface treatment experience a lower quench field (~27 MV/m) than obtained with other treatments (+40 MV/m) [4,5]. In addition, N-doped cavities show an increase in sensitivity to trapped magnetic flux when compared to other standard treatments [6,7].

In the context of LCLS-II High Energy upgrade and Fermilab R&D, this work presents a sequential study of new, optimized nitrogen doping surface treatments for the minimization of sensitivity to trapped magnetic flux and surface resistance while maximizing quench fields. In addition, TMAP studies were performed and cavity parameters are compared with trends found in [6] to gain insight on the mechanisms responsible for the increased performance that arises from these surface treatments. Lastly, the results of a 9-cell TESLA shaped Nb SRF cavity subject to one of these optimized nitrogen doping treatments is presented along with further possible insights on the mechanisms responsible for quench.

CAVITY PREPARATION

Three 1.3GHz niobium SRF cavities from RI and AES were subject to sequential surface treatments to ensure the same surface morphology. The treatments are outlined in Table 1. First, each of the cavities was baselined with the successfully implemented LCLS-II 2/6 N-doping surface treatment and tested at FNAL's vertical test stand (VTS). Then, the cavities underwent a 40 µm removal of the RF surface via electropolish (EP) to reset it. After this removal, the cavities received a new, optimized 2/0 N-doping treatment proposed by FNAL and were retested. Another 40 µm EP followed and the cavities were tested after receiving a final surface preparation, 3/60 N-doping, as proposed by Jefferson Laboratory. Note that all doping treatments were followed by a 5 µm EP removal to eliminate any nitrides that form on the surface. This leaves nitrogen to exist only as interstitial near the RF surface.

Table 1: Nitrogen Doping Treatments

2/6 Doping-Baseline	2/0 Doping-FNAL	3/60 Doping-JLab
800 C 3h in UHV	800C 3h in UHV	800 C 3h in UHV
800 C 2min 25 mTorr N	800 C 2min 25 mTorr N	800 C 3min 25 mTorr N
800C 6min UHV	N/A	800C 60min UHV
5 µm EP	5 µm EP	5 µm EP

RESULTS AND DISCUSSION

Sequential Study of Single Cells

The performance for one of the three single cell cavities post subsequent treatments outlined in Table 1 is summarized in Fig. 1.

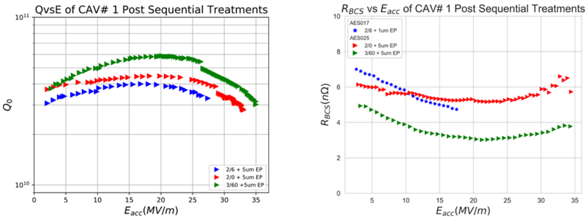

Figure 1: (Left) Quality factor vs accelerating gradient measurements and (Right) BCS resistance vs accelerating gradient of CAV# 1 post sequential treatments.

Cavity# 1 post the 2/6 doping LCLS II baseline gave a quench field of 27.5 MV/m with a max Q_0 of 4E10. After resetting the cavity surface and treating with 2/0 doping,

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the quench field increased by about 6 MV/m, giving a final quench field of 33 MV/m and a max Q_0 of about 4.4E10. Performing another RF surface reset and treating with 3/60 doping gave a quench field of an unprecedented value of 35 MV/m and Q_0 of 5.9E10. Note that the sudden drop in Q_0 at high gradients post 2/0 and 3/60 N-doping occurred after soft quench and is attributed to trapped flux. Processing increased the gradients to their final values. The BCS surface resistance for the cavity post 2/0 nitrogen doping is like that of a standard 2/6 nitrogen doped cavity. However, 3/60 doping gives a very low BCS resistance, achieving a minimum of 3.5 nΩ at 21 MV/m.

The quench field and Q_0 at 16 MV/m for each of the three cavities used in this sequential study of new nitrogen doping surface treatments are depicted in Fig. 2. Doping the three cavities with the baseline 2/6 treatment gives an average quench field of 24 MV/m and average Q_0 at 16 MV/m of 3.61E10 for the three cavities studied. Doping with 2/0 increases the average quench field and Q_0 at 16 MV/m up to 27 MV/m and 4.17E10. Lastly, 3/60 N-doping increases these values up to 30 MV/m and 4.92E10.

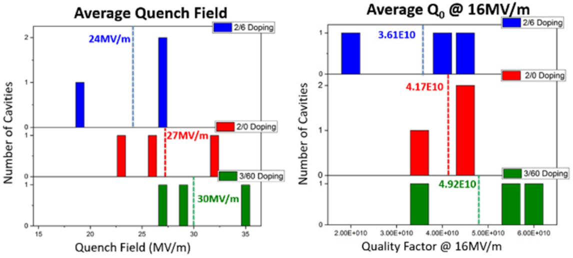

Figure 2: A histograms of (Left) the quench field and (Right) the quality factor at 16 MV/m for each of the three cavities studied post optimized N-doping surface treatments. Dashed lines denote average values.

TMAP Studies

Using the experimental thermometry mapping (TMAP) setup discussed in [8], cavity heating profiles post sequential optimized N-doping treatments were studied. TMAP profiles of CAV# 1 post 2/0 and 3/60 N-doping are presented in Fig. 3.

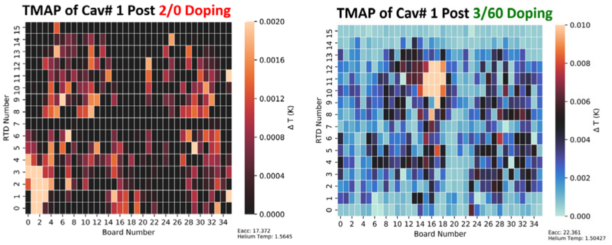

Figure 3: (Left) TMAP profile of CAV# 1 post 2/0 doping. (Right) TMAP profile of CAV# 1 post 3/60 doping. RTD Numbers 0, 7, and 15 coincide with the bottom iris, equator, and top iris of the cavity, respectively.

For the TMAP profile taken post 2/0 N-doping, the cavity quench occurred near the bottom iris, as seen from the local heating around the region of RTD Number 1, Board Number 1. Post 3/60 N-doping, the cavity quenched above the equator. Both tests showed thermal heating. Material studies are planned to better understand the origin of these local heating sites.

Sensitivity to Trapped Magnetic Flux

In addition to high Q_0 and high quench field, an optimal nitrogen doping treatment should introduce a minimal amount of surface resistance per mG of trapped field, or sensitivity to trapped magnetic flux. As such, in addition to the above Q_0 vs E_{acc} tests, the sensitivity of the cavities post optimized nitrogen doping surface treatments was also studied. To study the sensitivity to trapped magnetic flux, the cavities were first cooled down quickly to <1.5 K in zero field so that no magnetic flux was trapped. A Q_0 vs E_{acc} curve was then recorded. After, the cavities were warmed up and cooled down again but this time slowly and with an applied field of 20 mG. Q_0 vs E_{acc} curves was recorded once more. The experimental results are summarized in Fig. 4. Cavities that are 2/6 doped typically show a sensitivity to trapped magnetic flux of about 1.4 nΩ/mG at 16 MV/m whereas more heavily doped cavities see values closer to 1.8 nΩ/mG at 16 MV/m. Standard processing treatments such as the 120 C bake and electropolishing give sensitivity values of around 0.6 nΩ/mG at 16 MV/m. Cavities subject to the 2/0 optimized nitrogen doping surface treatment discussed in this paper have sensitivities that are like that of the 2/6 doping treatment. However, the 3/60 N-doping treatment gives sensitivity that is characteristic of a more heavily doped cavity.

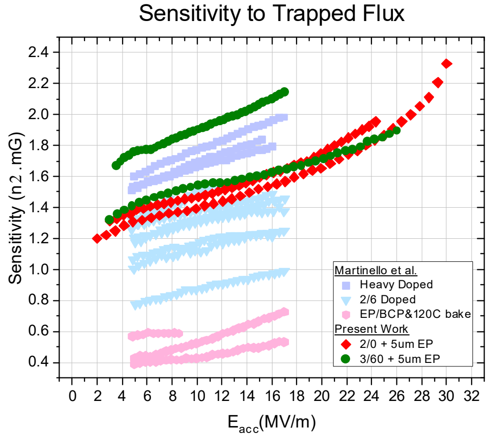

Figure 4: Sensitivity to trapped magnetic flux for different nitrogen doping treatments. Data shown in lighter symbol colours come from previous work [6]. "Heavier" doping treatments (i.e., higher nitrogen concentration) tend to have higher sensitivity to trapped magnetic flux than that of "lighter" doping.

Trends with Mean Free Path

The mean free path (MFP) in a superconductor is set by the distance between impurities and has been found to have some trend with cavity parameters, two of which are the temperature dependent BCS resistance and the sensitivity to trapped magnetic flux. The MFP of cavities was obtained by measuring the cavity resonant frequency as a function of temperature through warm up. The change in

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frequency was converted to a change in the penetration depth of the cavity. The data was fit with the SRIMP code [9]. The results are plotted in Fig. 5.

An optimal doping treatment should have a mean free path such that it minimizes the sensitivity to trapped magnetic flux and the BCS surface resistance.

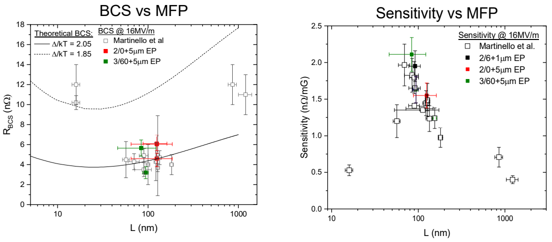

Figure 5: (Left) A plot of BCS surface resistance vs the mean free path near the RF surface of the cavity where supercurrents flows. The solid and dashed lines are the theoretical curves calculated using BCS theory for superconducting gap values of 2.05 and 1.85, respectively. (Right) A plot of sensitivity vs mean free path. Mean free path values of >800 nm come from EP cavities while for <20 nm the points come from 120 C bake cavities.

The 2/0 N-doping surface treatment gives a MFP of ~120 nm whereas 3/60 N-doping gives MFPs closer to ~90 nm. This suggests that although the BCS resistance of cavities subject to 3/60 N-doping is lower than that of 2/0 N-doping, the sensitivity to trapped magnetic flux is higher.

2/0 Doping of a 1.3 GHz 9-Cell Cavity

A 1.3GHz niobium 9-cell SRF cavity, CAV0017, was subject to the 2/0 N-doping surface treatment at FNAL. The Q_0 vs E_{acc} results are shown in Fig. 6. Although the cavity gave high Q_0, reaching a maximum value of ~3.6E10, the cavity quenched at 20 MV/m, lower than the average quench field obtained from the three single cell tests subject to the same surface treatment (27 MV/m). To gain insight on possible causes for early quench, the cavity was equipped with second sound and retested. In addition, mode measurements were performed, allowing for estimates of quench fields in each cell, which are shown in Table 2. Note that the field distributions in cells symmetric about cell five (cells one & nine, cells two & eight, etc.) are identical. One can see that cell number one, the cell closest to the fundamental power coupler (FPC), was quenching at 20 MV/m. In contrast, cell number five was quenching at 32.8MV/m. One possible hypothesis for this difference in quench fields among subsequent cells was that it could stem from variations in surface treatment. Upon investigation of the cavity treatment in the furnace, it was found that cell number one, the early quenching cell, was placed closest to the nitrogen inlet, which sits close to the door of the furnace.

To investigate this early quench further, the cavity surface was reset with a 60 μm EP and treated once again with the same 2/0 doping treatment as before; however, the cavity orientation was flipped such that the FPC faced the rear of the furnace, i.e., cell number nine was the cell closet to the furnace door/nitrogen inlet. The cavity was retested with second and mode measurements. The results are displayed in Fig. 6 and Table 2.

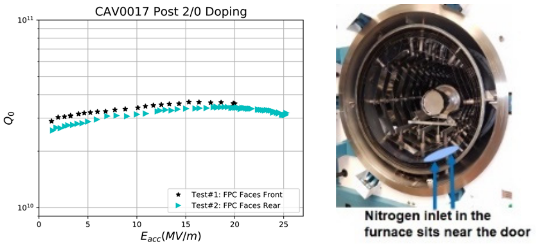

Figure 6: (Left) Q_0 vs E_{acc} of CAV0017 taken after 2/0 doping with different orientations in the furnace. (Right) Picture of FNAL furnace. Note that the nitrogen inlet sits close to the furnace door.

Table 2: Estimate of CAV0017 Quench Fields with Cavity Orientation in Furnace

Cell #	**Quench Field w/ FPC Toward Front of Furnace [MV/m]**	**Quench Field w/ FPC Toward Rear of Furnace [MV/m]**
1	20	>25.3
2	26.4	>25.3
3	>30	37.2
4	>27	>32.5
5	32.8	36.7
6	>27	>32.5
7	>30	>37
8	>26.4	>25.3
9	>20	25.3

After flipping the orientation of the cavity in furnace, the quenching cell moved from cell number one to cell number nine. In addition, the quench field increased by about 5 MV/m. This suggests that one possible cause for early quench could be due to some variation in surface impurity concentration between the two tests between the subsequent cells.

CONCLUSION

The above discussed optimized nitrogen doping surface treatments of single cell SRF cavities allow for higher accelerating gradients and quality factors than the already exceptional LCLS-II 2/6 N-doping treatment. For single cells, the new N-doping treatments maintain sensitivity to trapped magnetic flux similar that of the 2/6 baseline while maintaining or *decreasing* the BCS resistance. TMAP profiles show that CAV# 1 quenched off the equator for both N-doping treatments studied. Successful implementation of optimized nitrogen doping of 9-cell cavities requires further SIMS analysis to understand if differences in surface impurity structures between cells are a source of quench field limitations.

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