INVESTIGATION OF RF SURFACE RESISTANCE IN SUB-GHz SUPERCONDUCTING ELLIPTICAL CAVITIES PROCESSED WITH VARIOUS NITROGEN-DOPING SURFACE TREATMENTS*

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Abstract

Superconducting radio-frequency (SRF) cavity surface treatment with nitrogen-doping (N-doping) was a breakthrough in cavity processing which was found capable of increasing the cavity quality factor (Q_0) by more than a factor of 2 compared to standard electropolish (EP) surface treatments, as well as achieving a highly desirable anti-Q slope behavior, an increase of Q_0 with increasing accelerating field, in 1.3 GHz superconducting niobium cavities. N-doping has been extensively studied in 1.3 GHz cavities; however, a similarly significant increase in performance had not yet been observed in sub-GHz cavities. In this study, field-dependent BCS and residual resistances were measured in 644 MHz cavities for the FRIB energy upgrade with various surface treatments. The frequency dependence of the Q-slope was investigated by measuring BCS and residual resistances in the fundamental mode (FM) and a 1.45 GHz higher-order mode (HOM) in the same cavity. We will report effects of various N-doping surface treatments on the FM and HOM performance, including the achievement of Q_0 as high as 4.9×10^{10} at 17.5 MV/m in this class of SRF cavities.

INTRODUCTION

Maximizing the intrinsic quality factor (Q_0) is critical for superconducting radio-frequency (SRF) accelerators to minimize the cryogenic load and operating cost. Past studies of GHz-range SRF nitrogen-doped niobium cavities have shown both improved Q_0 and an "anti-Q slope"—an increase in Q_0 with accelerating gradient (E_{acc}) in the medium-field range ($E_{acc} \sim 2$ to 20 MV/m) [1].

Higher Q_0 and a possible anti-Q slope are of particular interest for the FRIB energy upgrade (FRIB400) project, which will make use of 5-cell elliptical niobium cavities operating at 644 MHz in CW at 2 K, with a goal of $Q_0 = 2 \times 10^{10}$ at an E_{acc} of 17.5 MV/m [2]. For cavities near 644 MHz, studies on the effects of mid-temperature baking (MTB) with 900 °C annealing have been found to increase Q_0 significantly [3]. Additionally, pioneering studies on 5-cell cavities were done using 800 °C N-doping, finding an increase Q_0, but by a lesser margin than for 1.3 GHz cavities [4]. However, the optimization of N-doping parameters has not yet been well-studied in this frequency range.

Additionally, studying the frequency dependence of the BCS resistance (R_{BCS}) and residual resistance (R_{res}) via measurements of different monopole modes in the same cavity, thus removing the dependence of cavity-to-cavity surface treatment variations, could provide guidance towards reducing Q-slope at 644 MHz.

CAVITY PROCESSING

Two FRIB energy upgrade single-cell cavities were used for this study (S65-901, S65-903). These cavities underwent N-doping of 800 °C and 900 °C, respectively. The process consisted of heat treatment at 800 °C or 900 °C for 3 hours in an ultra-high vacuum furnace (UHV) to reduce hydrogen concentration in the niobium bulk. For the last 2 minutes of the heat treatment, nitrogen was introduced at a pressure of 25 mTorr to promote diffusion of nitrogen into the cavity inner surface. After these 2 minutes, the nitrogen was pumped out, and the cavity was cooled back down to room temperature. This process is referred to as 800 °C or 900 °C 2N0-doping. The temperature and pressure for the 900 °C treatment of S65-903 are shown in Fig. 1. The N-doping treatment was preceded by bulk electropolishing (EP) and followed by light EP (5 µm). The post-treatment EP removes the harmful niobium nitride layer formed during N-doping, as the NbN layer significantly degrades Q_0 [1]. The cavities were then ultrasonic cleaned (USC), high-pressure rinsed (HPR), and clean-assembled for cold testing.

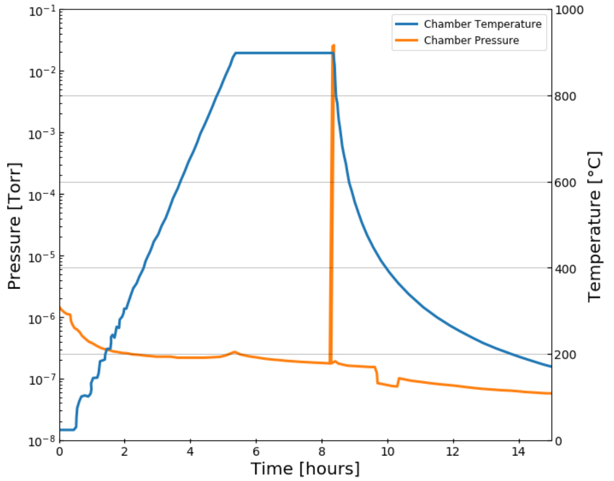

Figure 1: Chamber temperature and pressure during the 900 °C 2N0-doping procedure.

To measure Q_0 as a function E_{acc}, a "Q-curve", at cryogenic temperatures for both the TM_{010} FM (644 MHz) and

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the TM_{020} HOM (1.45 GHz), the cavity was equipped with variable input and pickup couplers, as shown in Fig. 2. The HOM coupling is much stronger than the FM coupling (Q_{ext} smaller by ~20 dB). the couplers bellows were adjusted to make $Q_{\mathrm{ext},1} \sim 10^{10}$ (input) and $Q_{\mathrm{ext},2} \sim 5{\cdot}10^{12}$ (pickup). The couplings were set after the cavity had been clean-assembled, pumped out, and removed from the clean room. Both the FM and HOM could thereby be measured without disassembly of the cavity.

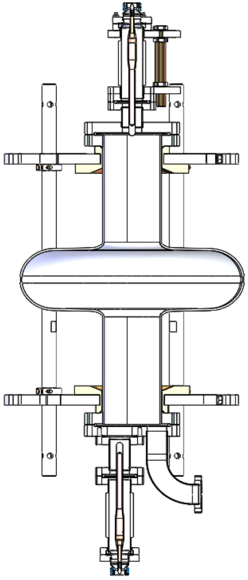

Figure 2: Cross-sectional view of the setup for vertical testing of a FRIB energy upgrade single-cell cavity with adjustable couplers.

The test Dewar is equipped with magnetic shields and a field cancellation coil, which enabled reduction of background magnetic field to about 1 mG. Additionally, a pair of Helmholtz coils was placed around the cavity to further reduce the background magnetic field. In the cold tests, the cavities were quickly cooled down across the niobium critical temperature, T_c, to maximize flux expulsion and thus minimize R_{res} [5, 6].

We measured Q-curves at 2 K and 1.7 K to determine the surface resistance (R_S). At 1.7 K, R_S is dominated by R_{res}. This allows us to decompose the R_S at 2 K into field-dependent R_{BCS} and R_{res} constituents.

RESULTS AND DISCUSSION

The FM 2 K Q-curves after baseline EP and two different N-doping treatments are shown in Fig. 3. In the 800 °C N-doping case, Q_0 is improved only at higher fields; in the 900 °C N-doping case, Q_0 is improved from low field up to the FRIB400 design goal (E_{acc} = 17.5 MV/m), with a high Q_0 of 4.9×10^{10} at the design field. Though providing a higher Q_0, the 900 °C N-doping resulted in a lower quench field. In the initial trial with 5 μm post EP, the quench limit was 16.5 MV/m. This however was later improved to 18 MV/m with an additional 4 μm EP (total 9 μm post EP).

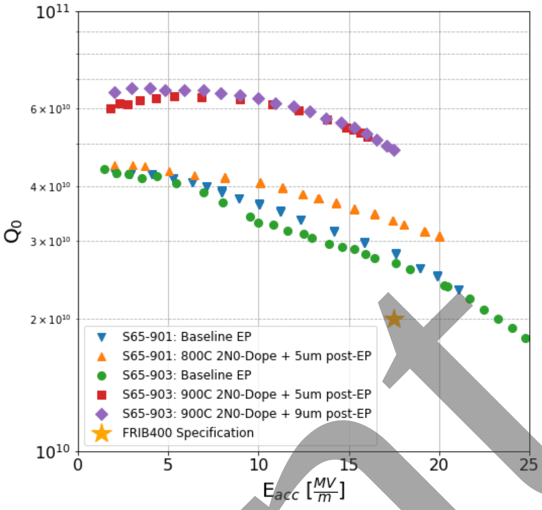

Figure 3: 2 K Q-curves for FRIB energy upgrade single-cell cavities after various treatments. The maximum fields after N-doping were limited by thermal breakdown.

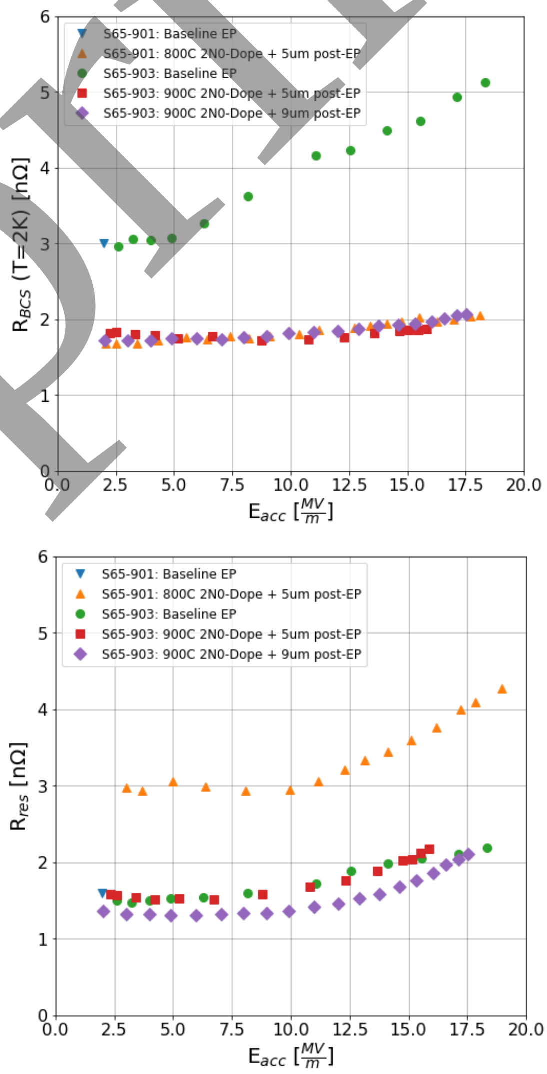

Figure 4: Field-dependent R_{BCS} (top) and R_{res} (bottom) for the cavities and treatments shown in Fig. 3.

To better understand the mechanism behind the increase in Q_0 after N-doping, the field dependences of R_{BCS} and R_{res} were compared in Fig. 4. N-doping consistently reduces R_{BCS} relative to baseline EP. The N-doping recipes have mixed impacts on R_{res}: R_{res} increases after N-doping at 800 °C, which can be explained as an increase in the sensitivity to trapped magnetic flux due to less optimal electron mean free path [7]. On the other hand, after 900 °C N-doping, R_{res} is similar to the baseline EP case, even though the sensitivity to trapped magnetic flux after 900 °C N-doping is higher than after 800 °C N-doping. This is due to the ability for the cavity to expel magnetic flux when transiting across T_c, allowing for minimal trapped flux to contribute to R_{res}. This enhanced flux expulsion is thought to be a result of a change in the grain structures from higher-temperature annealing [5].

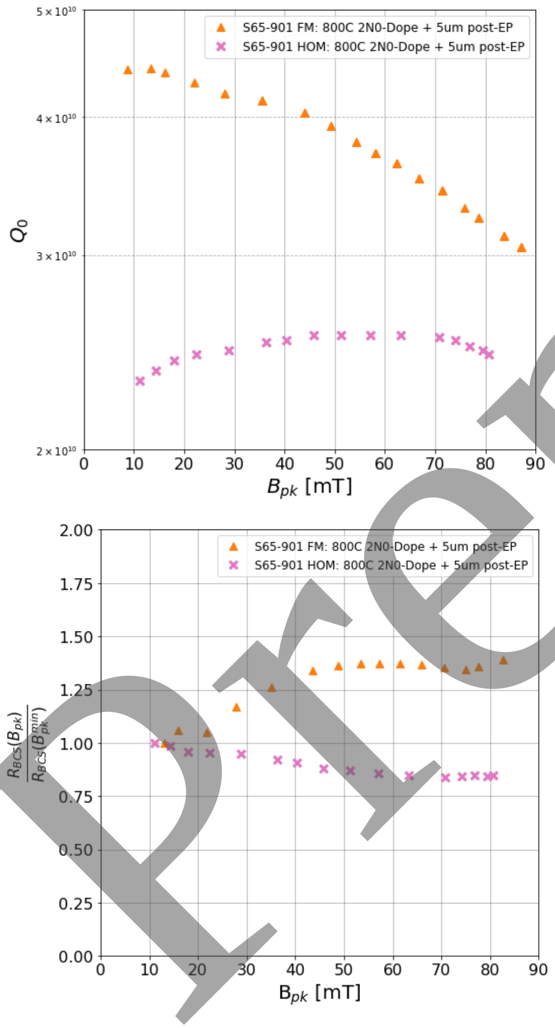

Figure 5: Q-curves for the FM and HOM after 800 °C N-doping + 5 µm post-EP (top). Corresponding R_{BCS} values at 2 K, normalized to their low field values (bottom). For the FM, B_{pk} = 80 mT corresponds to E_{acc} = 18 MV/m.

The FM and HOM Q-curves after 800°C N-doping are compared in Fig. 5 (top). For the 1.45 GHz HOM, anti-Q slope can been seen for a peak surface magnetic field (B_{pk}) between 10 and 60 mT, whereas the 644 MHz FM shows the typical decreasing Q_0 in this range. This difference in the Q-slopes is due to changes in R_{BCS}, as shown in Fig. 5 (bottom). These results are roughly consistent with a past study in which R_{BCS} was investigated for N-doped cavities with resonant frequencies ranging from 650 MHz to 3.9 GHz [8]. However, we investigated this frequency dependence on the same SRF surfaces, which allows any variations in cavity geometry or surface processing to be ruled out.

CONCLUSION AND OUTLOOK

Treatments on FRIB energy upgrade single-cell cavities were studied via cold testing after 800 °C and 900 °C N-doping. After 900 °C 2N0 doping, we measured $Q_0 = 4.9 \times 10^{10}$ at the design field of E_{acc} = 17.5 MV/m, a factor of 2.45 above the FRIB400 goal. Decomposition into R_{BCS} and R_{res} indicates that the Q_0 increase is due to a decrease in R_{BCS} without a reduction in R_{res}. Further studies with additional post EP after the 900 °C N-doping + 9 µm post-EP treatment are of interest, with the goal of increasing the quench field to at least a 10% safety margin, while maintaining the high Q_0.

A vertical test setup with adjustable couplers was developed for the single-cell cavities, which allowed us to study the impact of RF frequency on the field-dependent R_{BCS} after 800 °C 2N0 doping via measurements on multiple monopole modes. At 2 K, the 1.45 GHz HOM exhibits an anti-Q slope, while the 644 MHz FM does not. This difference in Q-slope is due to the field dependence of R_{BCS}. These observations, measured on the same RF surface, suggest that the Q-slope behavior has an intrinsic dependence on RF frequency.

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