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FIRST N-DOPING AND MID-T BAKING OF MEDIUM-β 644 MHz 5-CELL ELLIPTICAL SUPERCONDUCTING RF CAVITIES FOR MICHIGAN STATE UNIVERSITY'S FACILITY FOR RARE ISOTOPE BEAMS*

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Abstract

Two hadron linacs currently under development in the US, the PIP-II linac at Fermi National Accelerator Laboratory (FNAL) and the upgrade for Michigan State University's Facility For Rare Isotope Beams (FRIB), will employ 650 and 644 MHz $\beta \approx 0.6$ elliptical superconducting cavities respectively to meet their design energy requirements. The desired CW operational mode of these two linacs sets the cavity Q_0 requirements well above any previously achieved at this operating frequency and velocity, driving the need to explore new high-Q_0 treatments. The N-doping technique developed at FNAL and employed at an industrial scale recently to deliver the LCLS-II cryomodules [1,2] is a strong candidate for high-Q_0 treatments, but investigation is required to understand how to translate and optimize N-doping to the lower operating frequency and velocity regime. Herein we present the results of the first high-power RF tests of (2/0) (2 min N profusion 0 min annealing) N-doped and medium-temperature "Mid-T" baking tests [3-5] of the prototype FRIB400 644 MHz $\beta = 0.65$ 5-cell elliptical cavities [6]. Investigations of modifications to the electropolishing (EP) cathode required to accommodate the eccentric medium-beta cavity geometry in the post N-doping EP are also presented.

INTRODUCTION

The upgraded FRIB400 linac [7] aims to double the FRIB baseline end-energy from 200 to 400 MeV/u for the heaviest uranium ions, which equates to 1 GeV for protons. FRIB conventional facilities incorporated 80 meters of space in the linac tunnel reserved for energy upgrade cryomodules. Several SRF cavity designs were studied for their potential to meet this energy requirement in the available space in the most economical fashion, and it was ultimately concluded that a 5-cell 644 MHz cavity with $\beta_{opt} = 0.65$ is optimal for the energy upgrade [6]. Essentially, this design meets energy upgrade performance targets while minimizing heat load, number of additional cavities, and number of additional cryomodules. Two 5-cell prototypes of this design, serialized as S65-001 and S65-002, were ordered by FRIB and built at RI in Germany. These were delivered to FRIB/MSU in the fall of 2018, where preliminary RF testing commenced. This testing encompassed the following three "conventional" recipes: Buffered chemical polishing + 120°C baking (BCP+baking), electropolishing +120°C baking (EP+baking) and electropolishing without any baking (EP-only). The results of these tests have been reported previously [8, 9]. In summary, the EP-only trial delivered the best results, achieving $Q_0 = 2.3 \times 10^{10}$ at the desired operating gradient of 17.5 MV/m, achieving FRIB400 baseline requirements by 1.3 times. While these results are encouraging, we remain motivated to explore the application of novel N-doping recipes to these cavities, given the potential for significant gains in Q_0 that N-doping, or mid-T baking, offers [1, 3]. Gains in Q_0 by as much as a factor of two would significantly reduce the dynamic heat load, and in general, would further future, and wider, applications of medium- β superconducting RF cavities in science and industry.

RF SURFACE PROCESSING

S65-001 baseline EP consisted of a 150 μm bulk EP that was carried out at Argonne National Laboratory (ANL). The cavity was then baked FRIB's high-vacuum furnace for hydrogen degassing: first at 350°C for 12h, then at 600°C for 10 hours. After 20 μm EP, the cavity was used to test EP+120°C 48-hour bake. After this test, the cavity was "reset" with 30 μm EP plus 10 μm cold EP at ANL. S65-002 was similarly prepared to initially test the BCP+120°C 48-hour bake, and was similarly reset with 20 μm EP plus 10 μm cold EP at ANL. These EP preparations served as the baseline of comparison for each cavity to their future N-doped and mid-T baked performance.

After the EP baseline tests were conducted, S65-001 and S65-002 were then N-doped at FNAL facilities (2/0 doping at 800°C followed by 7 μm cold EP). Based on the initial performance of S65-001, it was suspected that post-doping EP had been incomplete, and an additional 5 μm of EP was conducted, which somewhat improved Q_0.

After the conclusion of the N-doping test, S65-001 was then EP-reset, and re-baselined. The cavity then underwent a further light EP at ANL, high pressure water rinse (HPR), 3 h 300°C "mid-T" bake in the FNAL vacuum furnace, then another HPR in the FNAL vacuum furnace, before final clean assembly to the vertical test insert at FNAL.

EP CATHODE MODIFICATION

Medium-β cavities have a relatively eccentric shape characterized by a high aspect ratio between the equator standoff distance (197 mm) and the cell length (142 mm). Equivalently, the sidewalls of this cavity type are relatively steep. The mechanical implications of steep sidewalls have been previously reported [1, 8, 9]. The implications of the

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larger standoff distance in medium-β cavities were explored initially by Bertucci et al [10] and are generally considered to be the results of higher electrolyte resistance due to increased electrolyte volume between the cavity equator and EP cathode axis. The current applied to the cavity thus becomes a function of position along the center axis of the cavity, and in turn so does the material removal, which is proportional to this current [10]. Uniformity of removal is critical in post N-doping EP, as incomplete removal of the surface niobium-nitrides will severely degrade cavity performance through increased residual resistance (R_0).

To counteract this effect, modifications were made to the EP cathode. Teflon masking was added in the iris region, and aluminum "doughnut" structures were mounted on the cathode centered on each equator region (Fig. 1). The single-cell version of the FRIB400 644 MHz cavity provided the opportunity to measure material removal over the entire cavity surface (Fig. 2), and revealed the cathode modifications produced satisfactory material removal uniformity (Fig. 3).

CAVITY TEST RESULTS

The Q_0 vs. E_{acc} curves for cavities S65-001 and S65-002 appear separately in Figs. 4 and 5. Cavity tests at FNAL were conducted in compensating Helmholtz coils, reducing background magnetic field to 1-2 mG or less. Cavity tests at FRIB were also conducted with a field-cancelling coil, which achieved a background magnetic field in the FRIB dewar of less than 1 mG [11]. The cryogenics plant for the FNAL vertical test stand is capable of reaching dewar temperatures of 1.5 K, where the residual resistance, R_0, can be assumed to be essentially the sole contributor to the surface resistance, R_s, measured at that temperature.

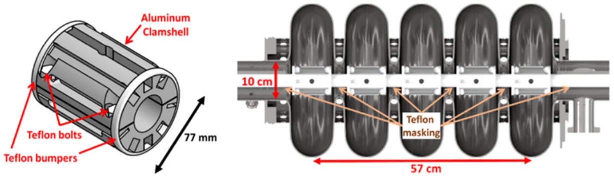

Figure 1: (right) Schematic of the aluminum "doughnut" structure assembled to the EP cathode in each equator region. (left) Schematic of the 5-cell cavity EP cathode, indicating the relative placement of the doughnuts and Teflon masking. Note that the radius of the aluminum doughnut is ultimately constrained by the beam-pipe radius, within reasonable safety tolerances for inserting and removing the EP cathode during the EP process.

BCS resistance, RBCS, and R0, are thus relatively easily decomposed as a function of cavity field level, and appear in Figs. 6 and 7.

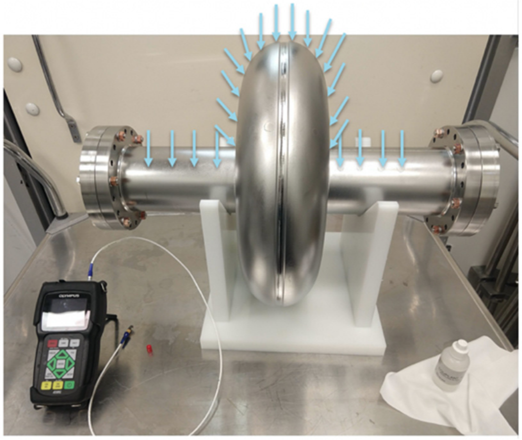

Figure 2: Blue arrows indicating ultrasonic thickness measurement points on the FRIB 644 MHz single-cell cavity.

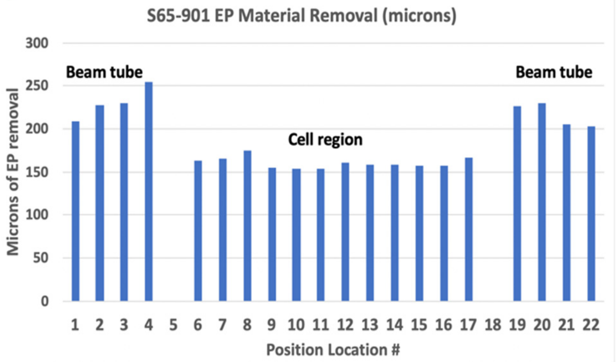

Figure 3: S65-901 (single cell) EP material removal in microns, in 20 locations across the cavity beam pipes and cell. The measurements in the cell region indicate that the goal of 150 µm is met with good uniformity regardless of location on the cell region, validating the EP cathode modifications.

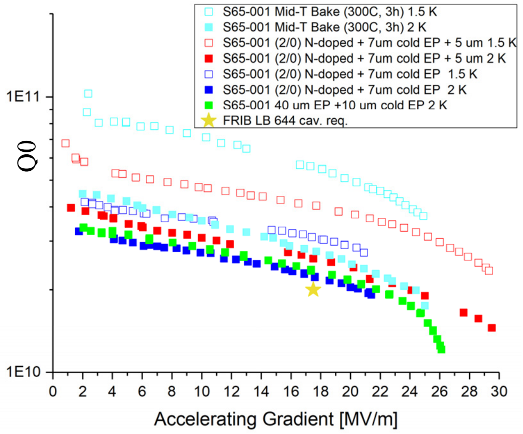

Figure 4: Q-curve of S65-001. Compared to the baseline EP (green). The 1st N-doping underperformed expectations (blue) so additional EP was undertaken (red). Cavity performance after EP reset and mid-T bake appears in cyan, with the best performance of $Q_0 = 2.7 \times 10^{10}$ at 17.5 MV/m.

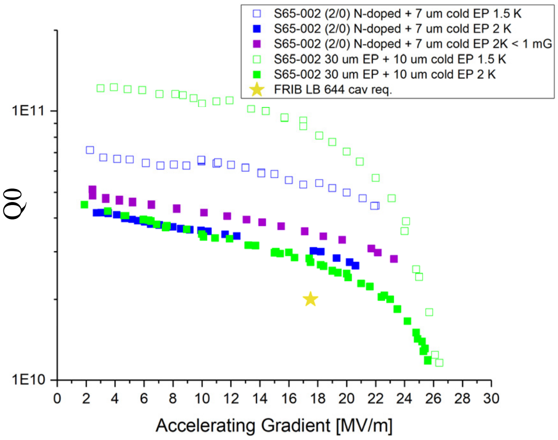

Figure 5: Q-curve of S65-002. The baseline EP test appears in green. The 1st N-doping test (blue) moderately exceeded the EP baseline performance, and was retested in the FRIB dewar with background magnetic field constrained below 1 mG, achieving the current world record for these cavities, $Q_0 = 3.5 \times 10^{10}$ at 17.5 MV/m [11].

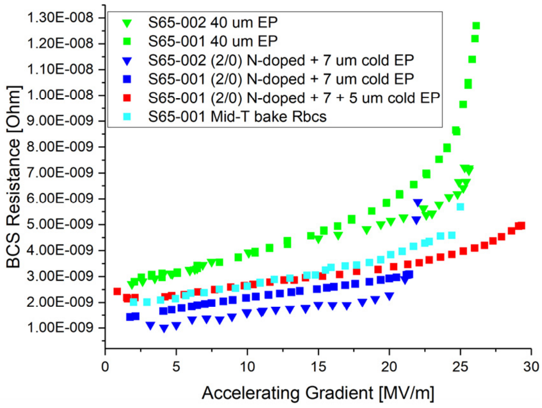

Figure 6: BCS resistance plotted as a function of cavity field for both cavities for each recipe test. Up to 60% reduction in BCS resistance was observed in the N-doping treatment. Mid-T baking also achieved a similar reduction in BCS resistance at moderate field levels.

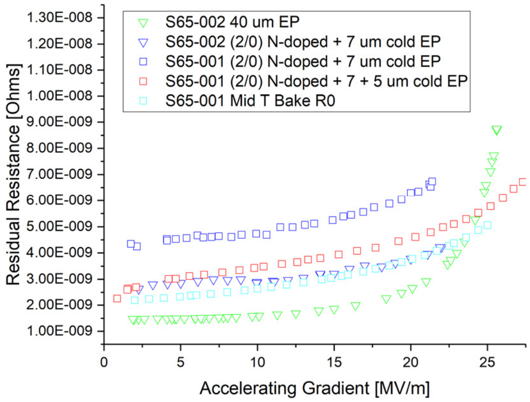

Figure 7: Residual resistance plotted as a function of cavity field for both cavities for each recipe test. (2/0) N-doping increased residual resistance by up to 30%, whereas mid-T baking was as much as 19% lower than the N-doping test.

CONCLUSION

(2/0) N-doping achieved $Q_0 = 3.5 \times 10^{10}$ at 17.5 MV/m, satisfying the FRIB400 baseline requirement by 1.75 times, and the PIP-II project baseline requirement for LB650 cavities at 16.8 MV/m by 1.47 times [12]. The BCS resistance was reduced by as much as 60%, but the residual resistance was increased by as much as 30% in some cases, highlighting the need to develop mitigation strategies for residual resistance in N-doped cavities. Mid-T baking produced $Q_0 = 2.7 \times 10^{10}$ at 17.5 MV/m, satisfying FRIB400 requirements by 1.41 times. Where the BCS resistance was similar to that seen in the N-doping test, the residual resistance was reduced by the Mid-T bake compared to the N-doping test by 19%. These results are encouraging given the relative gains in simplicity and cost of the mid-T baking treatment, and motivate further investigation of this treatment with the single-cell version of the FRIB400 644 MHz medium-β cavity, just recently made available for testing.

ACKNOWLEDGEMENTS

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