ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB030

MEDIUM TEMPERATURE FURNACE BAKING OF LOW-BETA 650 MHz FIVE-CELL CAVITIES*

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Abstract

Medium Temperature baking of low beta 650 MHz cavities was conducted in a UHV furnace. A systematic study of cavity surface resistance components, residual and BCS, was conducted, including analyzing surface resistance due to trapped magnetic flux. Cavities showed an average 4.5 nano-ohm surface resistance at 17 MV/m under 2 K, which meets PIP-II specifications with a 40% margin. The results provided helpful information for the PIP-II project to optimize the cavity processing recipe for cryomodule application. The results were compared to the 1.3 GHz cavity that received a similar furnace baking.

INTRODUCTION

Mid-T baking of superconducting radio-frequency (SRF) cavities is a technique that aims to improve the quality factor (Q_0) of these cavities by dissolving the oxides on the niobium surface. SRF cavities are widely used in particle accelerators and require high Q_0 values to reduce the cryogenic cost and increase the beam energy. Mid-T baking involves heating the cavity at a temperature range of 250–400 °C under an ultra-high vacuum for several hours. It was conducted in situ, where the 1.3 GHz cavity was fitted with testing hardware and was actively evacuated during the baking process resulting in higher Q_0 values and anti-Q-slope behavior [1]. A carefully cleaned and protected cavity can be placed in a UHV furnace without testing hardware. A naturally formed oxide layer provided the source of oxygen to diffuse into the niobium bulk. As the cavity is re-exposed to air after the furnace baking, a new oxide layer is formed. The cavity can then be cleanly prepared for a cold test without the need for chemical processing. The cavity performance was similar to that of the in-situ baked cavities [2]. Similar baking was conducted for 650 MHz cavities [3]. Mid-T baking in a furnace is more convenient and easier than other techniques, such as nitrogen doping [4] or infusion [5], and can also simplify the surface processing of SRF cavities.

The PIP-II linac is a high-power proton accelerator under construction, enabling the world's most intense neutrino beam for the DUNE experiment [6]. It consists of an 833 MeV superconducting linear accelerator. An important linac section includes 23 cryomodules operating at 2 K with continuous wave (CW) mode [7]. Nine cryomodules use the 650 MHz 5-cell cavities with β values of 0.61, known as LB650.

* Work supported by Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics
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The LB650 cavities will be operated at a comparatively higher E_{acc} of 16.9 MV/m and a high $Q_0 = 2.4\times10^{10}$. To achieve such high-performance specifications, high Q processing of N-doping [4], N-infusion [5], and Mid-T baking [1] were evaluated. With the successful electropolishing (EP) optimization [8], the mid-T baked cavity showed promising results during the LB650 preproduction cavity qualification. Two different baking temperatures were studied. The impact of the temperature on the flux trapping was evaluated and could guide further studies of the temperature dependence of cavity Q_0 in a real-world cryomodule.

In addition, some benefits of mid-T baking related to cavity testing will be discussed.

EXPERIMENT

Cavity Processing

Bare cavities were fabricated by a commercial vendor, who used the niobium and NbTi material procured by Fermilab. The cavity's inner surface received 40 µm BCP before the final welding during bare cavity fabrication. There were no following chemistry or heat treatments after the final welding at the vendor's facilities.

Once the cavity arrived at Fermilab, the incoming inspection was conducted, and cavity wall thickness was measured. Cavities received 120 µm bulk EP, followed by UHV furnace treatment to reduce hydrogen concentration in niobium bulk. The heat treatment temperature was either 800 °C or 900 °C for three hours. Cavities then were tuned to achieve 98% field flatness before 40 µm EP, where the final 20 µm was performed at a cold temperature (12 °C). The cavities were high-pressure water rinsed and assembled in a clean room for cold tests.

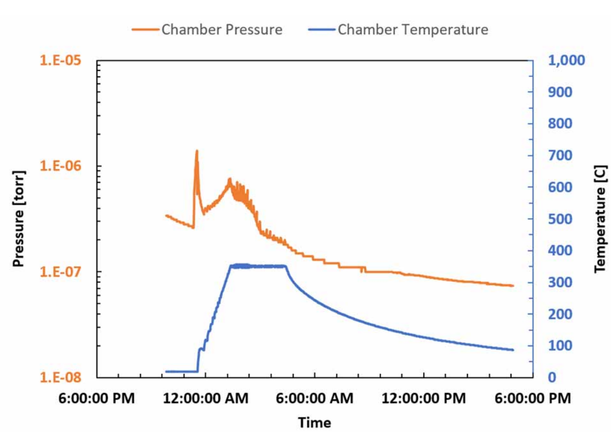

Figure 1: Cavity temperature and furnace pressure during the mid-T baking.

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Once the cavity passed the post-EP baseline test, they were high-pressure water rinsed and received the Mid-T furnace baking. Two cavities received 300 °C mid-T bak-ing, and the other two received 350 °C mid-T baking, as shown in Fig. 1. After the furnace baking, the cavities were high-pressure water rinsed and assembled in a clean-room for cold tests.

Cavity Testing

Cavities were tested in two vertical test pits. The two cryostats in the pits have slightly different residual mag-netic fields. The field was carefully mapped, and an aver-age residual field in the cavity location was used for mag-netic field compensation. Two Helmholtz coils were used for each cavity. Due to the spatial effect, the compensation coil can only compensate for a fixed value. Since the field map showed the residual magnetic field was nonuniform, the residual field on the cavity wall will not be at zero, as shown in Fig. 2. Some magnetic fields could be trapped during the cavity cooldown if the material was not properly heat-treated to expel flux efficiently. In those cavities that did not expel flux, an average residual field trapping after the field compensation and fast cool-down were used using the

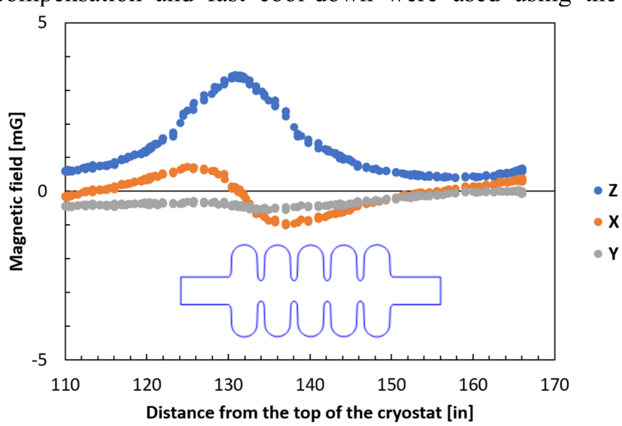

Figure 2: Magnetic field measured at one of five lines par-allel to the cryostat axis. Z denotes the axial direction of the cryostat. The cavity center is located 140-in below the top of the cryostat.

Cavities were tested at 2 K, 1.8 K, 1.6 K, and 1.45 K at the same accelerating gradients with intervals of one MV/m. Quench was avoided for most of the cavity tests. When the cavity experienced a quench, a remeasurement of the Q_0 vs. E_{acc} was conducted to subtract the trapped flux effect. The Q curves at different temperatures were used to conduct the surface resistance decomposition studies.

After the cavity Q curves were measured, the cavities were warmed up to > 20 K, and a field of ~10 mG field was applied using the compensation coils. The cavities were cooled down slowly to ensure the magnetic field was fully trapped during the superconducting transition. Q curves were then measured. By subtracting the surface resistance from the tests after the field compensation, one can obtain the surface resistance sensitivity to the trapped flux. For cavities that didn't expel flux well, the residual magnetic field in the cryostat can be used to calculate the residual resistance without the contribution of the trapped flux.

Cavities were also thermally cycled between 4.5 K and higher temperatures under 100 mG applied field to meas-ure the flux expulsion efficiency [9].

RESULTS AND DISCUSSION

Flux Expulsion Efficiency

Two cavities were treated with hydrogen de-gas at 800 °C for three hours, and another two cavities were at 900 °C. The four cavities were made with the same nio-bium materials. The 800 °C treated cavities do not expel the magnetic field like those two 900 °C treated cavities, despite the fast cool down in the vertical testing cryostat. Figure 3 compares the magnetic flux expulsion efficiency for the two heat treatment temperatures. The two 800 °C treated cavities showed the increased residual resistance that will be discussed later.

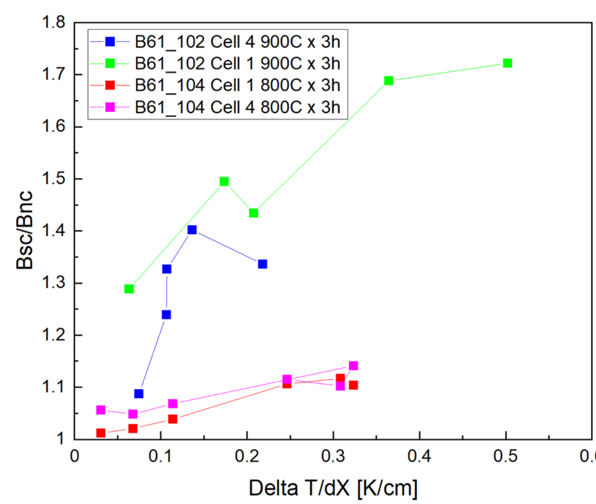

Figure 3: Flux expulsion efficiency of the two heat treat-ment temperatures.

Q_0 Measurement of Mid-T Baked Cavities

All cavities were tested with EP-only baseline pro-cessing. Three cavities met the bare cavity acceptance cri-teria, as shown in Fig. 4. One cavity (B61C-EZ-101) ex-perienced a lower accelerating gradient due to a welding defect. After the EP-only processing and vertical tests, two cavities were treated at 300 °C for three hours. The other two cavities were treated at 350 °C for three hours. That cavity with the welding defect received local mechanical polishing to remove the defect, followed by a 60 µm EP. There was no vertical test before the mid-T baking at 350 °C. The higher quality factor was achieved for three cavities except for the cavity with the welding defect, as shown in Fig. 5. Both cavity gradient and Q factor dropped below that of the EP-only processing. An optical inspection showed that mechanical polishing lines and smaller pits caused by the polishing media remained on the surface.

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Table 1: Cavity Surface Resistance Measured at 16.9 MV/m

Cavity	H-degas (°C)	Mid-T furnace (°C)	R_res (nΩ)	R_res_dew (nΩ)	R_bcs (nΩ)	Rs_total (nΩ)
B61C-EZ-102	900	300	3.1±0.2	0.0	1.4±0.2	4.3±0.4
B61C-EZ-103	900	300	2.1±0.2	0.0	2.4±0.2	4.5±0.4
B61C-EZ-101	800	350	4.7±0.3	0.9±0.1	2.6±0.3	8.4±0.7
B61C-EZ-104	800	350	2.1±0.2	1.5±0.1	2.7±0.3	6.3±0.6

A further 40 µm EP followed by furnace hydrogen degas heat treatment and 10 µm light EP qualified the cavity for EP-only baseline processing. The cavity will be mid-T baked soon.

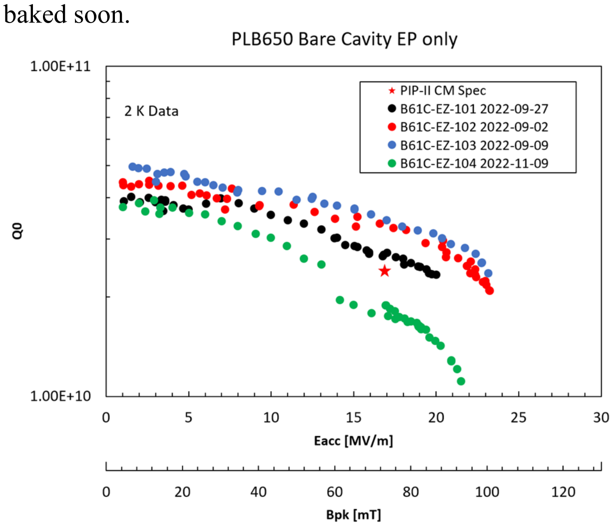

Figure 4: Q curves of cavities with EP-only baseline processing.

Table 1 shows the cavity surface resistance at 16.9 MV/m obtained from low-temperature measurements. The term R_res_dew represents the surface resistance contributed by the small amount of the residual magnetic field in the cryostat that was trapped in the cavity wall for the two cavities treated at 800 °C.

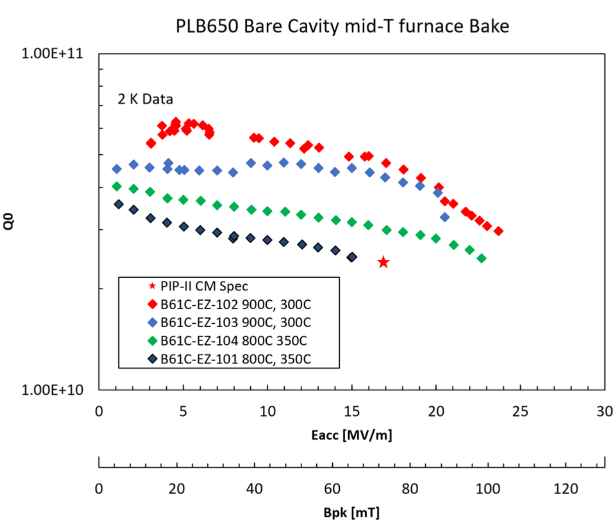

Figure 5: Q curves of cavities with mid-T baking.

For the 350 °C mid-T baked cavities, the BCS component of the surface resistance was slightly higher than that of the 300 °C mid-T baked cavities. After removing the trapped flux effect, the residual resistance showed similar results between the two different mid-T baking temperatures.

Surface Resistance Sensitivity to the Trapped Flux

Q curves were measured before and after the flux trapping to calculate the surface resistance sensitivity to the trapped flux. Figure 6 shows one cavity result that the flux trapping sensitivity increases as the accelerating gradient increases.

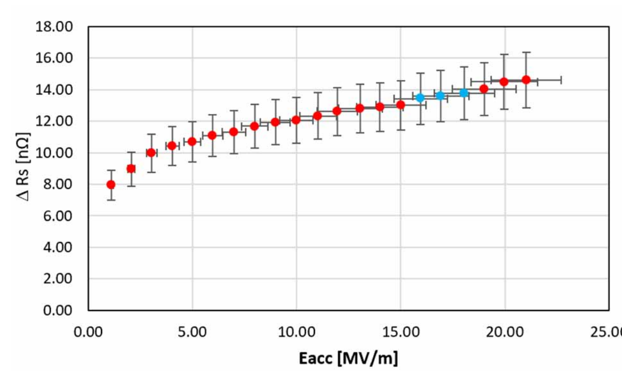

Figure 6: Surface resistance contributed by a trapped flux of 11.4 mG. The blue dots were used to average the sensitivity at the PIP-II cavity's nominal operating gradient at 16.9 MV/m.

The flux sensitivity was measured for all four cavities. The result is summarized in Table 2.

Table 2: Surface Resistance Sensitivity to the Trapped Flux at 16.9 MV/m

Cavity	Mid-T furnace (°C)	Flux sensitivity (nΩ/mG)
B61C-EZ-102	300	2.03 ± 0.52
B61C-EZ-103	300	1.95 ± 0.66
B61C-EZ-101	350	1.02 ± 0.50
B61C-EZ-104	350	1.20 ± 0.56

Multipacting and Mode-mixing

During the cavity vertical testing, no multipacting was observed for the four cavities regardless of the processing differences, such as EP only, EP plus 120 °C baking, 300 °C, or 350 °C baking. The absence of multipacting was surprising since CST microwave simulations predicted that the multipacting would be widespread 5 MV/m to 15 MV/m with a peak near 11 MV/m [10]. Mode-mixing was consistently experienced, except for the cavities treated at 350 °C. Further studies will be needed to understand the benefit of 350 °C baking.

CONCLUSION

The mid-T baking studies of the four LB650 cavities showed that the mid-T baking showed the process improved the cavity quality factor that was comparable to the nitrogen doping process. Two different temperatures of mid-T baking were compared. While the 350 °C mid-T baked cavities showed a slightly higher BCS resistance than that of the 300 °C mid-T baked cavities, the trapped flux sensitivity was nearly double that of the 300 °C mid-T baked cavities. Considering the potential magnetic field trapping in a cryomodule, the 350 C mid-T baking temperature could be preferred for a linac's overall higher quality factor.

The results from the four 650 MHz cavities were consistent with the mid-T baking results of the 1.3 GHz 1-cell cavity [2].

ACKNOWLEDGMENTS

This manuscript has been authored by Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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