Quality Factor Enhancement of 650 MHz Superconducting Radio-Frequency Cavity for CEPC

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Abstract: Medium-temperature (mid-T) furnace baking was conducted at 650 MHz superconducting radio-frequency (SRF) cavity for circular electron positron collider (CEPC), which enhanced the cavity unloaded quality factor (Q_0) significantly. In the vertical test (2.0 K), Q_0 of 650 MHz cavity reached 6.4×10^{10} at 30 MV/m, which is remarkably high at this unexplored frequency. Additionally, the cavity quenched at 31.2 MV/m finally. There was no anti- Q -slope behavior after mid-T furnace baking, which is characteristic of 1.3 GHz cavities. The microwave surface resistance (R_s) was also studied, which indicated both very low Bardeen–Cooper–Schrieffer (BCS) and residual resistance. The recipe of cavity process in this paper is simplified and easy to duplicate, which may benefit the SRF community.

Keywords: medium-temperature furnace baking; SRF cavity; quality factor; gradient; surface resistance

Citation: Sha, P.; Pan, W.; Zhai, J.; Mi, Z.; Jin, S.; Liu, B.; Dong, C.; He, F.; Ye, L.; He, X.; et al. Quality Factor Enhancement of 650 MHz Superconducting Radio-Frequency Cavity for CEPC. *Appl. Sci.* **2022**, *12*, 546. <https://doi.org/10.3390/app12020546>

Academic Editor: Satyabrata Kar

Received: 15 December 2021

Accepted: 4 January 2022

Published: 6 January 2022

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1. Introduction

SRF cavities made of niobium are broadly adopted for the modern accelerators, which have demonstrated much higher Q_0 and lower R_s than cavity made of copper. Here, R_s is the electrical resistance of surface layer to current, and inversely proportional to Q_0 of SRF cavity. Recently, the technology of medium-temperature (mid-T, 250–400 °C) baking is used to increase Q_0 of 1.3 GHz cavities successfully, which dissolves the oxides in the surfaces of niobium [1–3]. It is more convenient and easier than nitrogen doping/infusion [4–6]. At the Fermi National Accelerator Laboratory (FNAL), the 1.3 GHz single-cell cavity was evacuated with pump and received mid-T baking at 300 °C in an oven. The highest Q_0 of cavities mid-T baked exceeded 5×10^{10} (at 2.0 K). The mid-T furnace baking of 1.3 GHz single-cell cavities also succeed at High Energy Accelerator Research Organization (KEK), which was conducted in a vacuum furnace. The Institute of High Energy Physics, Chinese Academy of Sciences (IHEP) also successfully developed mid-T furnace baking of 1.3 GHz single-cell and nine-cell cavities.

For low-frequency (<1 GHz) elliptical cavities used in colliders and proton/neutron sources [7–9], Q_0 usually decreases more quickly along with accelerating gradient than that of 1.3 GHz cavities. Nitrogen doping could increase Q_0 of 650 MHz single-cell $\beta = 0.9$ cavity for the Proton Improvement Plan II (PIP-II) project to 7×10^{10} at medium fields of approximately 15–25 MV/m [7]. However, there are very few mid-T baking attempts of low-frequency cavities, which may demonstrate differences with 1.3 GHz as well as nitrogen doping [7,10]. Thus, the mid-T furnace baking of 650 MHz cavity for CEPC was carried out at IHEP, which obtained high Q_0 and low R_s successfully.

2. The Process of Mid-T Furnace Baking

The cavity investigated in this paper is a 650 MHz single-cell $\beta = 1$ SRF cavity for CEPC, which is made of fine-grain niobium with high residual-resistivity-ratio (RRR > 300). The ratio of the peak surface magnetic field (B_{peak}) to accelerating gradient (E_{acc}) is approximately 4.2. Firstly, the 650 MHz cavity received bulk electro-polishing (EP) process with a total removal of $\sim 315 \mu\text{m}$, where the temperature was below 25°C all the time. There was no high-temperature annealing for hydrogen outgassing before or after EP, because we wanted to simplify the recipe of mid-T furnace baking, which combines high-temperature annealing and mid-T furnace baking at a later stage. Therefore, the 650 MHz cavity received high-pressure rinsing (HPR), assembly, low-temperature baking (120°C for 48 h) and vertical test directly after bulk EP [1]. In the vertical test of EP baseline (blue icon), the 650 MHz cavity quenched at a very high gradient of 37.5 MV/m ($B_{\text{peak}} = 158 \text{ mT}$) with Q_0 of 1.4×10^{10} in Figure 1, which indicated smooth and defect-free surfaces of the cavity. However, the Q value was slightly lower than the CEPC vertical test (VT) spec of 4.0×10^{10} at 22 MV/m . The behavior of Q -slope may result from hydrogen diffused in the cavity during EP process. The radiation began to increase at 33 MV/m , so field emission was low during the vertical test. R_s of the 650 MHz cavity (blue icon) increased exponentially along with the accelerating gradient in Figure 2, which is typical for cavity EP processed [7,9]. Hence, the cavity was considered qualified to receive mid-T furnace baking.

Figure 1. Vertical test results of 650 MHz SRF cavity (Blue: processed with EP; Red: processed with mid-T furnace baking).

Afterwards, the 650 MHz cavity was subjected to high-temperature annealing at 900°C for 3 h (hydrogen degassing) [11,12], and the following light EP was cancelled. Then, the cavity was exposed to air for 3 days in cleanroom (oxidation). Finally, it received mid-T furnace baking at 300°C for 3 h [13] as well as 1.3 GHz nine-cell cavity [3], which is shown in Figure 3. During the entire process, both cavity flanges were covered with niobium foils, which had been chemically polished, to keep the cavity inner surface from dust. The process of mid-T furnace baking was key to improve Q_0 of 650 MHz cavity. Prior to mid-T furnace baking, the furnace was pumped adequately to obtain ultimate vacuum ($< 5 \times 10^{-6} \text{ Pa}$). The highest pressure of furnace vacuum was about $3.5 \times 10^{-5} \text{ Pa}$ during the process of mid-T furnace baking (Figure 4), which was maintained with two cryopumps.

After cooling down, the vacuum pressure was about 2.5×10^{-6} Pa, and the cavity was taken out.

Figure 2. Surface resistance (R_s) of 650 MHz SRF cavity (Blue: processed with EP; Red: processed with mid-T furnace baking).

Figure 3. Setup of the mid-T furnace baking for 650 MHz cavity.

Figure 4. Temperature and vacuum curves during mid-T furnace baking.

3. Vertical Test after Mid-T Furnace Baking

Following mid-T furnace baking, the 650 MHz cavity was subjected to HPR and assembled with flanges. Then, it received a vertical test immediately, while the usual low-temperature baking was cancelled. The cavity demonstrated significantly high Q_0 at all fields during the vertical test, which is shown in Figure 1. Extremely high Q_0 was achieved at low fields, which exceeded 1.0×10^{11} . The cavity also exceeded the CEPC vertical test spec of 4.0×10^{10} at 22 MV/m. The Q_0 reached 6.3×10^{10} at 31 MV/m, which was much higher than 2.1×10^{10} of EP baseline. There was no field emission during the test, and the cavity quenched at 31.2 MV/m ($B_{\text{peak}} = 131$ mT) finally. Furthermore, there was no anti- Q -slope behavior, which is usual for 1.3 GHz cavities after mid-T baking [1–3].

The surface resistance after mid-T furnace baking is depicted in Figure 2, which was remarkably lower than EP baseline. It was about 2.5 nΩ at low fields and 4.5 nΩ at high fields, which was significantly low and increased slowly as a function of gradient.

The 650 MHz cavity also received vertical tests at lower temperatures (1.5–2.0 K) to investigate the composition of R_S , which consists of BCS resistance (R_{BCS}) and residual resistance (R_{res}). The value of R_{BCS} increases exponentially as a function of temperature. However, R_{res} remains consistent when the temperature increase from 1.5 to 2.0 K [14].

$$R_S = R_{\text{BCS}} + R_{\text{res}} \quad (1)$$

$$R_{\text{BCS}} = A \frac{f^2}{T} \exp\left(-\frac{\Delta(T)}{kT}\right) \quad (2)$$

Here, k is the Boltzmann constant, T is the temperature, f is the frequency of SRF cavity, 2Δ is the energy gap of niobium. A is the coefficient that depends on the superconducting parameters of niobium, such as mean free path, coherence length and London penetration.

R_{BCS} at 2.0 K (Figure 5) and R_{res} (Figure 6) of 650 MHz cavity were calculated according to Equations (1) and (2), and compared with 1.3 GHz cavity, which adopted the same recipe of mid-T furnace baking. R_{res} remained < 2 nΩ at both low and high fields in Figure 6, which is rather low at this frequency. It was less than 1 nΩ at low fields. R_{BCS} was 2 nΩ constantly at low fields, and slightly increased as a function of accelerating gradient above 20 MV/m in Figure 5. The decrease in R_{BCS} as a function of accelerating gradient for 1.3 GHz cavity [1–3] did not appear for 650 MHz cavity. It confirms that mid-T furnace baking could not reverse R_{BCS} at the frequency of 650 MHz. Therefore, the anti- Q -slope behavior cannot be observed at 650 MHz cavity mid-T furnace baked. Similarly, nitrogen doping could not reverse R_{BCS} of 650 MHz cavity, either [7,15].

Figure 5. BCS resistance (R_{BCS}) of 650 MHz cavity and 1.3 GHz cavity (at 2.0 K), which both received mid-T furnace baking.

Figure 6. Residual resistance (R_{res}) of 650 MHz cavity and 1.3 GHz cavity, which both received mid-T furnace baking.

4. Conclusions

Mid-T furnace baking was attempted at 650 MHz single-cell cavity, which achieved a state-of-the-art high Q_0 at the accelerating gradient of 30 MV/m. Extremely low R_S of 3.4 nΩ at 25 MV/m was demonstrated, while the typical value of R_S is 5–10 nΩ.

Nitrogen doping is another kind of processing for SRF cavities, which can also improve Q_0 . It is also carried out in a vacuum furnace along with the injection of nitrogen gas by thermal diffusion, which is followed by light EP to remove the niobium nitrides inside cavity surface [16]. Compared with nitrogen doping, mid-T furnace baking is much easier and more convenient. These studies can help to enhance the performance and comprehension of large elliptical (<1 GHz) superconducting cavities, which are broadly used by synchrotron light sources, proton/neutron sources and high-energy colliders.

Author Contributions: Conceptualization, P.S. and B.L.; Data curation, S.J. and Z.M.; Formal analysis, P.S.; Funding acquisition, P.S. and W.P.; Investigation, P.S. and J.Z.; Methodology, J.Z.; Project administration, W.P.; Resources, F.H.; Software, S.Z., L.Y. and X.H.; Supervision, P.S.; Visualization, C.D.; Writing—original draft, P.S.; Writing—review and editing, P.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant Nos. 12075270, 11505197), Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB25000000) and the Platform of Advanced Photon Source Technology R&D.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable.

Acknowledgments: The authors would like to thank Beijing HE-Racing Technology Co., Ltd.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Posen, S.; Romanenko, A.; Grassellino, A.; Melnychuk, O.; Sergatskov, D. Ultralow surface resistance via vacuum heat treatment of superconducting radio-frequency cavities. *Phys. Rev. Appl.* **2020**, *13*, 014024. [\[CrossRef\]](#)
2. Ito, H.; Araki, H.; Takahashi, K.; Umemori, K. Influence of furnace baking on Q-E behavior of superconducting accelerating cavities. *Prog. Theor. Exp. Phys.* **2021**, *2021*, 071G01. [\[CrossRef\]](#)
3. He, F.; Pan, W.; Sha, P.; Zhai, J.; Mi, Z.; Dai, X.; Jin, S.; Zhang, Z.; Dong, C.; Liu, B.; et al. Medium-temperature furnace baking of 1.3 GHz 9-cell superconducting cavities at IHEP. *Supercond. Sci. Technol.* **2021**, *34*, 095005. [\[CrossRef\]](#)
4. Gonnella, D.; Aderhold, S.; Burrill, A.; Daly, E.; Davis, K.; Grassellino, A.; Grimm, C.; Khabiboulline, T.; Marhauser, F.; Melnychuk, O.; et al. Industrialization of the nitrogen-doping preparation for SRF cavities for LCLS-II. *Nucl. Instrum. Methods Phys. Res. A* **2018**, *883*, 143–150. [\[CrossRef\]](#)
5. Grassellino, A.; Romanenko, A.; Trenikhina, Y.; Checchin, M.; Martinello, M.; Melnychuk, O.S.; Chandrasekaran, S.; A Sergatskov, D.; Posen, S.; Crawford, A.C.; et al. Unprecedented quality factors at accelerating gradients up to 45MVm^{-1} in niobium superconducting resonators via low temperature nitrogen infusion. *Supercond. Sci. Technol.* **2017**, *30*, 094004. [\[CrossRef\]](#)
6. Liu, B.; Sha, P.; Dong, C.; He, F.; Pan, W.; Mi, Z.; Zhai, J.; Jin, S.; Dai, J.; Li, Z.; et al. Nitrogen doping with dual-vacuum furnace at IHEP. *Nucl. Instrum. Methods Phys. Res. A* **2021**, *993*, 165080. [\[CrossRef\]](#)
7. Martinello, M.; Bice, D.J.; Boffo, C.; Chandrasekaran, S.K.; Ereemeev, G.V.; Furuta, F.; Grassellino, A.; Melnychuk, O.; Sergatskov, D.A.; Wu, G.; et al. Q-factor optimization for high-beta 650 MHz cavities for PIP-II. *J. Appl. Phys.* **2021**, *130*, 174501. [\[CrossRef\]](#)
8. Zheng, H.; Sha, P.; Zhai, J.; Pan, W.; Li, Z.; Mi, Z.; He, F.; Zhang, X.; Dai, J.; Han, R.; et al. Development and vertical tests of 650 MHz 2-cell superconducting cavities with higher order mode couplers. *Nucl. Instrum. Methods Phys. Res. A* **2021**, *995*, 165093. [\[CrossRef\]](#)
9. McGee, K.; Kim, S.; Elliott, K.; Ganshyn, A.; Hartung, W.; Metzgar, E.; Ostroumov, P.; Popielarski, L.; Taylor, A.; Xu, T.; et al. Medium-velocity superconducting cavity for high accelerating gradient continuous-wave hadron linear accelerators. *Phys. Rev. Accel. Beams* **2021**, *24*, 112003. [\[CrossRef\]](#)
10. McGee, K. New Results on N-Doping Applied to 5-Cell Elliptical $\beta = 0.65$ 644 MHz Cavities. Tesla Technology Collaboration Meeting 2021. Available online: <https://indico.desy.de/event/27572/contributions/94301/attachments/63521/> (accessed on 10 November 2021).
11. Trenikhina, Y.; Romanenko, A.; Kwon, J.; Zuo, J.-M.; Zasadzinski, J.F. Nanostructural features degrading the performance of superconducting radiofrequency niobium cavities revealed by TEM and EELS. *arXiv* **2015**, arXiv:1503.02046.
12. Ciovati, G.; Myneni, G.; Stevie, F. High field Q slope and the baking effect: Review of recent experimental results and new data on Nb heat treatments. *Phys. Rev. Spec. Top.-Accel. Beams* **2010**, *13*, 022002. [\[CrossRef\]](#)
13. Delheusy, M.; Stierle, A.; Kasper, N.; Kurta, R.P.; Vlad, A.; Dosch, H.; Antoine, C.; Resta, A.; Lundgren, E.; Andersen, J. X-ray investigation of subsurface interstitial oxygen at Nb/oxide interfaces. *Appl. Phys. Lett.* **2008**, *92*, 101911. [\[CrossRef\]](#)
14. Padamsee, H. *RF Superconductivity: Science, Technology, and Applications*; WILEY-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2009.
15. Martinello, M.; Aderhold, S.; Chandrasekaran, S.K.; Checchin, M.; Grassellino, A.; Melnychuk, O.; Posen, S.; Romanenko, A.; Sergatskov, D.A. Advancement in the Understanding of the Field and Frequency Dependent Microwave Surface Resistance of Niobium. In Proceedings of the SRF2017, Lanzhou, China, 17–21 July 2017; pp. 364–367. Available online: <https://accelconf.web.cern.ch/srf2017/papers/tuyaa02.pdf> (accessed on 10 November 2021).
16. Grassellino, A.; Romanenko, A.; Sergatskov, D.; Melnychuk, O.; Trenikhina, Y.; Crawford, A.; Rowe, A.; Wong, M.; Khabiboulline, T.; Barkov, F. Nitrogen and argon doping of niobium for superconducting radio frequency cavities: A pathway to highly efficient accelerating structures. *Supercond. Sci. Technol.* **2013**, *26*, 102001. [\[CrossRef\]](#)