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# REALIZATION OF ACCELERATING GRADIENT LARGER THAN 25 MV/m ON HIGH-Q 1.3 GHz 9-CELL CAVITIES FOR SHINE*

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*Abstract*

We present our studies on the optimized nitrogen-doping and medium-temperature baking recipes applied on 1.3GHz SRF cavities, aiming at meeting the requirements of the SHINE project. The optimized nitrogen-doping process resulted in achieving a $Q_0$ of over $4.0 \times 10^{10}$ at medium field and a maximum accelerating gradient exceeding 35 MV/m on single-cell cavities, and a $Q_0$ of over $2.8 \times 10^{10}$ at medium field and a maximum accelerating gradient exceeding 26 MV/m in 9-cell cavities. For 1.3 GHz 9-cell cavities subjected to medium-temperature baking, $Q_0$ values exceeding $3.5 \times 10^{10}$ at 16 MV/m and maximum accelerating gradients surpassing 25 MV/m were achieved. These studies provide two options of high-Q recipes for SHINE cavities. The treatment processes of cavities and their vertical test results are described in this paper.

## INTRODUCTION

Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is a new hard-XFEL facility under construction in China. This facility is designed to accelerate electron beams to 8 GeV by 600 1.3 GHz 9-cell cavities working in continuous wave mode with an intrinsic quality factor ($Q_0$) of $2.7 \times 10^{10}$ at an accelerating gradient of 16 MV/m [1]. In recent years, two prominent approaches, nitrogen doping (N-doping) [2–6] and medium-temperature (mid-T) baking [7–11], have been extensively studied as key recipes for enhancing the $Q_0$ value of SRF cavities.

Starting from 2021, we have been conducting experimental cavity treatments utilizing the SHINE facilities for SRF cavity surface treatments on the platform located in Wuxi City, China (referred to as the Wuxi Platform, see Fig. 1). This paper presents the achievements obtained through the implementation of N-doping and mid-T baking treatments on 1.3 GHz SRF cavities.

## OPTIMIZATION OF NITROGEN DOPING PROCESS

A single-cell cavity, TF63, was treated using the N-doping recipe [12] that we studied before at the Wuxi platform. The vertical test result at 2 K of TF63 after the first N-doping at the Wuxi Platform is shown in Fig. 2. TF63 reaches

Figure 1: Newly constructed SRF cavity surface treatment platform (main hall).

$3.8 \times 10^{10}$ at 16 MV/m but quenches at 18.9 MV/m. In order to improve its maximum accelerating gradient, an optimized N-doping process [13] was attempted on TF63. In this N-doping process, the furnace was heated to 800 °C and maintained for 30 min to stabilize the temperature. Then, nitrogen was injected directly for 3 min, and the cavity was annealed for 60 min in vacuum and cooled naturally. Thereafter, TF63 was tested at SARI and obtained interesting results, which are shown in Fig. 2. TF63 reaches $4.1 \times 10^{10}$ at 16 MV/m, with a maximum accelerating gradient larger than 35 MV/m (admin limit to avoid quench), which is almost doubled compared with that at the first round N-doping. Another single-cell cavity S02 was processed as the same optimized N-doping recipe and realized the similar performance.

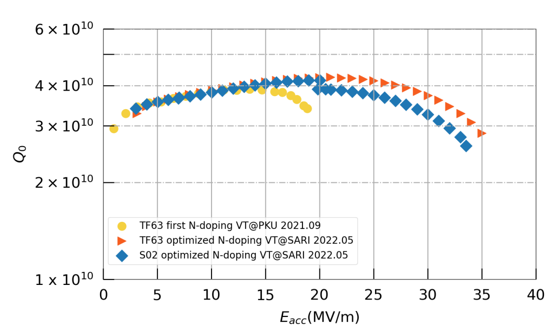


Figure 2: Vertical test results at 2 K of the two single-cell cavities, S02 and TF63.

Following the successful N-doping of single-cell cavities, two 9-cell cavities, HJ005 and HJ006, underwent subsequent treatment using the same recipe, as outlined in Table 1 for the second treatment of HJ005 and HJ006. Vertical test results at

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Table 1: History and Recipes for the Related Cavities Treated in the Wuxi Platform

| Cavity | Recipe | VT |
|---|---|---|
| TF63 (1st treat.) | EP 60 µm (cold)+900 °C/3 h+3/60@800 °C+EP 10 µm (cold) | PKU 2021.09 |
| (2nd treat.) | EP 50 µm(cold)+800 °C/0.5 h+3/60@800 °C+EP 10 µm (cold) | SARI 2022.05 |
| S02(1st treat.) | EP 50 µm (cold)+800 °C/0.5 h+3/60@800 °C+EP 10 µm (cold) | SARI 2022.05 |
| HJ005(1st treat.) | BCP 100 µm+EP 100 µm(cold)+900 °C/3 h+3/60@800 °C+EP 10 µm (cold) | PKU 2021.11 |
| (2nd treat.) | EP 50 µm (cold)+ 800 °C/0.5 h+3/60@800 °C+EP 10 µm (cold) | SARI 2022.04 |
| HJ006(1st treat.) | BCP 60 µm (cold)+EP 140 µm (cold)+900 °C/3 h +3/60@800 °C+EP 10 µm (cold) | PKU 2021.11 |
| (2nd treat.) | EP 70 µm (cold)+800 °C/0.5 h+3/60@800 °C+EP 10 µm (cold) | SARI 2022.04 |
| S04(1st treat.) | EP 20 µm (cold)+400 °C/3 h | PKU 2021.09 |
| (2nd treat.) | 300 °C/3 h without EP | PKU 2022.02 |
| NF33(1st treat.) | EP 60 µm (cold)+300 °C/3 h | PKU 2021.09 |
| (2nd treat.) | EP 100 µm (cold)+900 °C/3 h +exposure to air +300 °C/3 h | SARI 2023.04 |
| TF62(1st treat.) | EP 40 µm (cold)+300 °C/3 h | SARI 2021.12 |
| (2nd treat.) | EP 20 µm (cold)+800 °C/3 h +exposure to air +300 °C/3 h | SARI 2022.08 |
| SS003(1st treat.) | EP 50 µm (cold)+900 °C/3 h +exposure to air +300 °C/3 h | SARI 2023.04 |

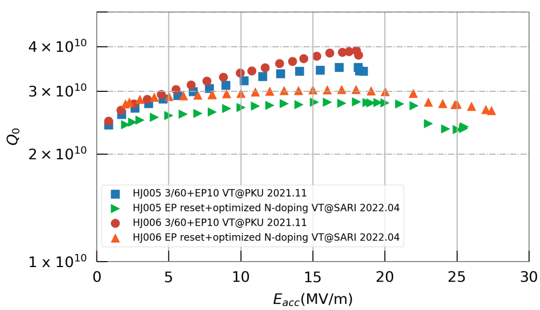


Figure 3: Vertical test results at 2 K of two 9-cell cavities, namely, HJ005 and HJ006, after optimized N-doping.

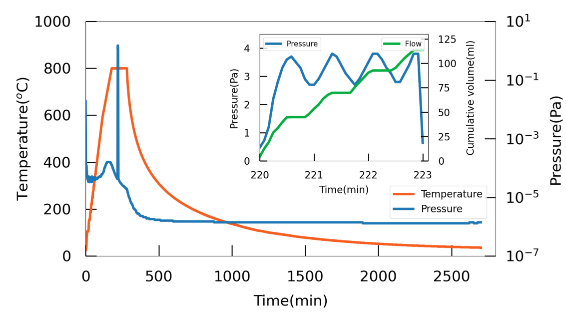


Figure 4: Temperature and pressure monitored during the typical optimized N-doping recipe.

2 K revealed a notable enhancement in the maximum gradient for both 9-cell cavities. The maximum gradient exhibited a clear increase from 18 MV/m to approximately 26 MV/m, as illustrated in Fig. 3. The high-temperature vacuum baking and N-doping processes were conducted in the same furnace for single-cell cavities. During the N-doping process, the temperature (indicated by the red line) and the pressure (indicated by the blue line) within the vacuum furnace were monitored. Simultaneously, the cumulative volume of nitrogen infused into the furnace was recorded by the flow meter installed in the infusion pipe (represented by the green line). Figure 4 presents the typical monitored pressure and temperature data during the optimized N-doping process.

# RESEARCH ON MID-T BAKING RECIPES

We also conducted some explorations in the field of mid-T baking. Firstly, three 1.3 GHz single-cell cavities, S04, NF33, and TF62, underwent mid-T baking experiments. These cavities had undergone surface treatment experiments previously, so the surfaces were first reset using EP and then subjected to mid-T baking. NF33 and TF62 cavities were directly baked at 300 °C after EP treatment, while S04 cavity was baked at 400 °C for comparison. Subsequently, vertical tests were conducted at PKU and SARI. The vertical test results of these three cavities are summarized in the Fig. 5. From the vertical test results, it can be observed that the S04 cavity baked at 400 °C exhibited a $Q_0$ value of only $2.7\times10^{10}$ at 16 MV/m, while NF33 had a $Q_0$ value of $5.7\times10^{10}$ and TF62 had a $Q_0$ value of $4.3\times10^{10}$ at 16 MV/m.

Subsequently, after the vertical testing of the S04 cavity, we performed necessary cleaning only on the outer surface and immediately proceeded with a mid-T baking at 300 °C. It was observed that the $Q_0$ value significantly improved to $3.7\times10^{10}$. Therefore, we selected 300 °C as the treatment temperature for mid-T baking, which is consistent with the results obtained by laboratories such as KEK [8] and IHEP [9].

Meanwhile, we also carried out a segmented mid-T baking process. As a control, we initially selected the TF62 cavity and performed EP to reset the inner surface. Considering its previous multiple rounds of high-temperature heat treatments, we utilized a treatment process involving an 800 °C high-temperature baking, exposure to air, and a subsequent 300 °C mid-T baking. Vertical test was conducted at SARI, and the result is shown in the Fig. 6. This cavity

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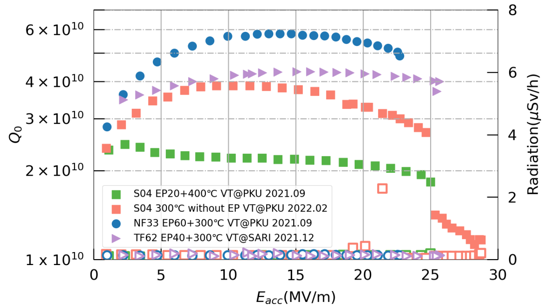


Figure 5: Vertical test results at 2 K of the three single-cell cavities, namely, S04, NF33 and TF62.

exhibited field emission at around 17 MV/m, resulting in a decrease in $Q_0$. At 16 MV/m, the $Q_0$ value was measured at $4.6 \times 10^{10}$, which is comparable to the results obtained from direct mid-T baking. The cavity achieved a maximum accelerating gradient of 30.5 MV/m.

Therefore, we additionally selected two new cavities, SS003 and NF33, both made of fine-grain niobium. These two cavities underwent bulk EP, followed by a 900 °C high-temperature baking for degassing and enhancing magnetic flux exclusion capability. After around 48 h of exposure to air, they underwent a 300 °C mid-T baking. The vertical test results of these two cavities are shown in the Fig. 6 below. The $Q_0$ values at 16 MV/m were measured at $3.6 \times 10^{10}$ and $3.7 \times 10^{10}$, respectively. The maximum accelerating gradients were both around 30 MV/m, limited by quench.

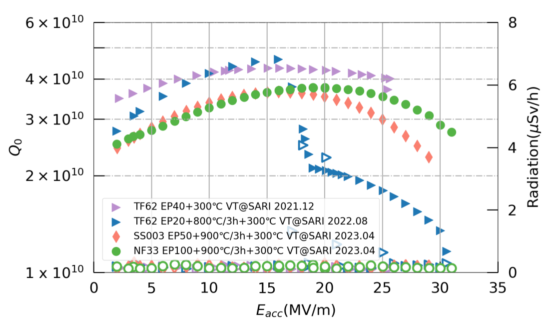


Figure 6: Vertical test results at 2 K of the three single-cell cavities, S04, NF33 and TF62.

## VERTICAL TEST RESULTS OF SMALL-BATCH PRODUCTION

Based on the previous experimental results, we conducted small-batch experiments on several prototype cavities. Among them, seven jacketed cavities processed by an international manufacturer using N-doping technology were utilized. The process flow is shown in Fig. 7 (a), and the $Q_0$ values at 16 MV/m were all greater than $2.7 \times 10^{10}$. The maximum accelerating gradients exceeded 21 MV/m. Regarding the mid-T baking process, we also treated five 9-cell cavities at the Wuxi platform following the process flow depicted in Fig. 7 (b). The maximum accelerating gradients of all these cavities exceeded 25 MV/m, and their $Q_0$ values at 16 MV/m were all greater than $2.7 \times 10^{10}$. However, some cavities exhibited multipacting quenches [14] at around 12 MV/m and 20 MV/m, leading to a decrease in $Q_0$. The vertical test results at 2 K are shown in the Figs 8 and 9. All these cavities reach the design specifications of SHINE.

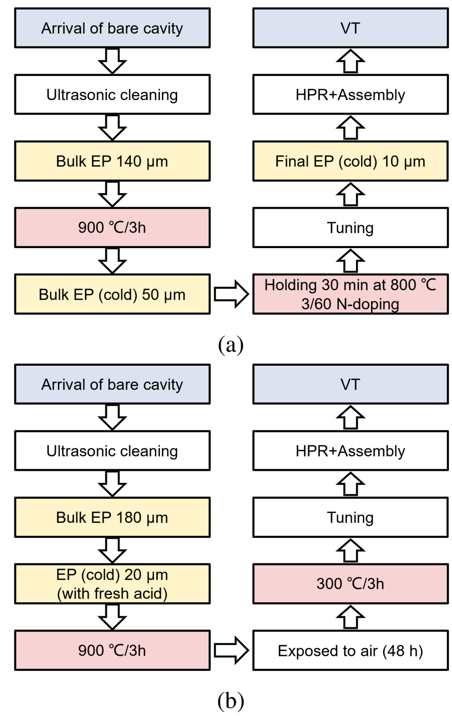


Figure 7: (a) Process sequence of optimized N-doping treatment. (b) Process sequence of mid-T baking treatment.

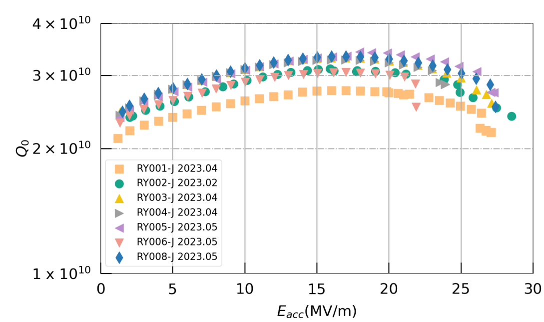


Figure 8: Vertical test results at 2 K of seven 9-cell cavities treated with the optimized N-doping recipe at an international cavity manufacturer.

## SUMMARY

Based on the newly co-constructed Wuxi platform, we conducted a series of experiments involving N-doping and mid-T baking treatments and preliminarily applied the optimized process to the production of small-batch superconducting cavities for SHINE project. Currently, the majority of the cavities have met the specifications of SHINE. In near fu-

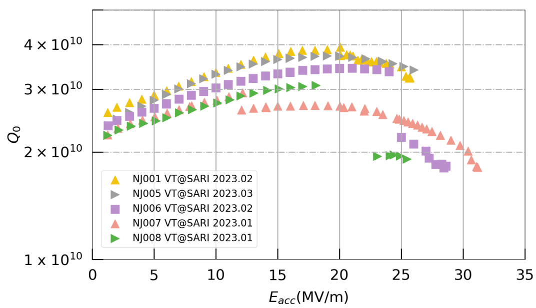


Figure 9: Vertical test results at 2 K of all the five 9-cell cavities treated with the mid-T baking recipe.

ture, we will continue to study the treating process to further enhance the yield of high Q and high gradient cavities.

## ACKNOWLEDGEMENTS

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