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DEVELOPMENT OF NITROGEN-DOPING TECHNOLOGY FOR SHINE*

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Abstract

The Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is under construction, which needs six hundred 1.3 GHz cavities with high quality factor. In this paper, we present the newest studies on single-cell cavities with nitrogen doping and cold EP treatment, showing an obvious improvement compared with the previous results.

INTRODUCTION

Nitrogen-doping (N-doping) has been approved not only to eliminate the medium-field Q-slope (MFQS) of superconducting RF cavities, but also to significantly increase the intrinsic quality factor [1]. This processing technique has become an important treatment for superconducting cavities production. For the SHINE accelerator, one of the main challenge is to achieve for the cavities performance $Q_0 = 2\sim3\times10^{10}$ at $E_{acc} = 14\sim18$ MV/m, with max $E_{acc}>19$ MV/m. So the nitrogen doping process is considered for the cavity production. After N-doping treatment, to eliminate nitrides that form on the surface, the cavities need light EP process. According to the studies by Fermilab [2,3], they developed a new EP method called "cold EP" with very low temperature, which can achieve a regular, periodic, deeply modulated current wave form during electropolishing of cavities to achieve smoother surface.

In this paper, we report the study results using the 3/60 recipes that was explored by Jefferson lab [4]. Besides, we also report the improvements on small EP devices to pursue better cavity surface.

SURFACE TREATMENTS

In this study, all the single-cell cavities experienced a bulk EP firstly, followed by a high temperature baking and a light EP process as baseline treatment. Then these cavities were treated by N-doping at 800 °C and finished with light EP. Figure 1 shows the process sequence of these 1.3 GHz single-cell cavities.

Previous studies by Fermilab and Jefferson lab [5] have shown that colder EP can reduce the etching phase of the doped and undoped niobium and create a smoother surface. Here we tried to use cold EP method to treat the N-doped cavity. In order to reach that, we updated the EP tool at OSTEC, Ningxia.

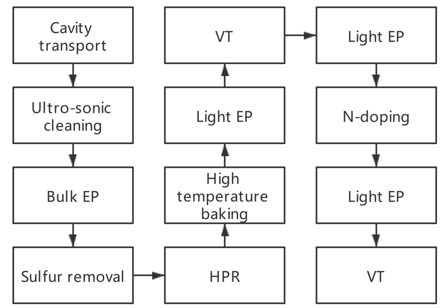

Figure 1: Process sequence for the N-doped single-cell cavities.

Simple Cold EP Tool

Figure 2 shows the updated simple EP device at Ningxia, which was originally built by OSTEC and Peking University [6]. Outside cooling water pipes were added to further decrease the temperature of cavity outside wall to below 15 °C and the temperature of electrolyte to below 10 °C during the EP process. The EP parameters are shown in Table 1. And, this simple "cold EP" was applied as the light EP method in this study.

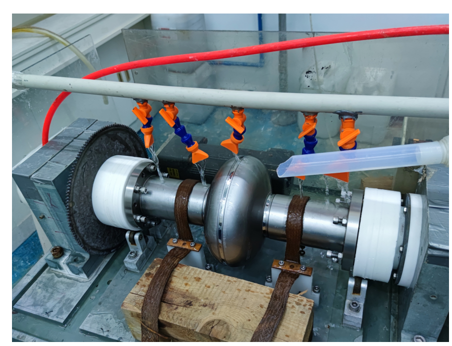

Figure 2: Simple cold EP tool.

Table 1: Cold EP Parameters

Parameters	Value
Electrolyte temperature	<10 °C
Cell temperature	<15 °C
Cavity rotation speed	1 rpm
Electrolyte flow rate	3~5 L/min

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Table 2: Surface Treatments Histories

Cavity	HT for 3h	N-doping at 800 °C	Light polishing [μm]
S02 (1st treat.)	800	3/60	EP 5
(2nd treat.)	–	–	EP 10
(3rd treat.)	–	–	EP12
NF33	900	3/60	EP 10
L01 (1st treat.)	800	3/60	EP 5
(2nd treat.)	–	–	EP 8
(3rd treat.)	–	–	EP 15

Note: The cavity S02 and L01 got 20/30 recipes at 2018. And S02 experienced 975 °Cbaking at that time. In this study we resetted these cavities with heavy EP and treated them with new baseline recipes.

Nitrogen Doping Experiments

After the EP baseline treatments, these cavities experienced 3/60 doping. When the vacuum in furnace reaches 2×10^{-4} Pa, the temperature is firstly ramped to 800 or 900 °C, holding for 3 hours in high vacuum. Secondly, the temperature is lowered to 800 °C, and the nitrogen is introduced at this time for 3 min, followed by an annealing at 800 °C for 60 min. Finally, the furnace is cooled to around 50 °C to fetch out the cavity. This process is shown in Fig. 3. After the N-doping, these cavities are electropolished with the simple cold EP device. Then, ultrasonic cleaning with detergent and HPR are used to remove sulfur. The recipes applied on these 1.3 GHz single-cell cavities have been shown on Table 2.

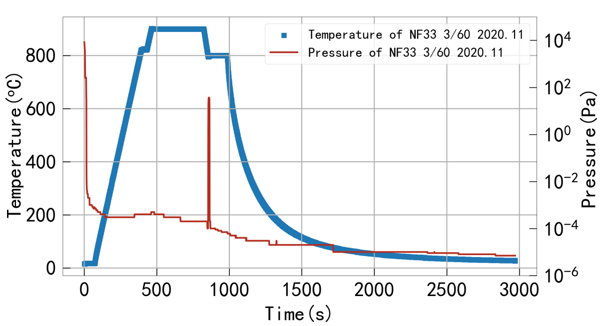

Figure 3: The temperature and pressure of cavity NF33 during N-doping process.

VERTICAL TEST RESULTS

Before applying 3/60 recipe, the large-grain (LG) cavity L01 and fine-grain (FG) cavity S02 had experienced heavy N-doping with 20/30 recipes [7]. Therefore, the L01 and S02 firstly underwent a heavy EP to reset the surface. Then, these cavities received a 3/60 N-doping treatment. Followed by a light cold EP to eliminate the nitrides on the inner surface. In order to study the optimum removal thickness of light EP after N-doping, cavity L01 received total removal of 5 μm, 8 μm and 15 μm, respectively, and cavity S02 got total removal of 5 μm, 10 μm and 12 μm, respectively. The vertical test results, finished at Peking University, are shown in Figs. 4 and 5. For the cavity L01, the 8 to 15 μm light EP shows no big difference on the value of Q_0 under 19 MV/m. However, the 15 μm one shows much higher quench field, which approaches 28.6 MV/m with $Q_0 = 5.2 \times 10^{10}$ at 16 MV/m. The sudden decrease in Q_0 between 17 and 23 MV/m, accompanied with a slight increase of radiation, is likely due to multipacting. The fine-grain cavity S02 gets higher Q_0 after 10 μm light EP treatment, and further improved after another 2 μm, which reaches 3.9×10^{10} at 16 MV/m and quenches at 22.5 MV/m.

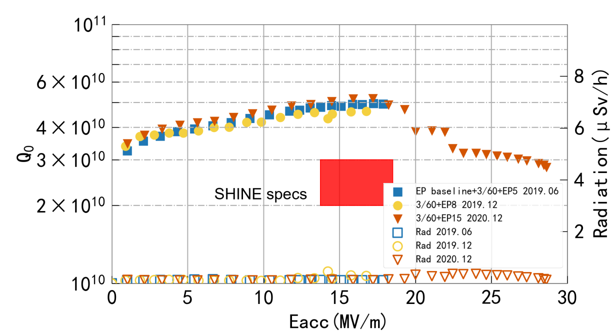

Figure 4: Vertical test results of LG single-cell cavity L01.

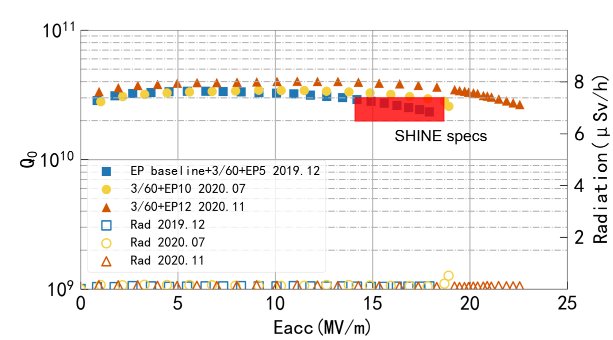

Figure 5: Vertical test results of FG single-cell cavity S02.

The new fine-grain cavity NF33 that we first did an EP baseline treatment quenches at around 27 MV/m with reason-

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able quality factor. Afterwards, we added the 3/60 N-doping and 10 µm light EP. The Q_0 in medium field is doubled, around 4.6×10^{10} at 16 MV/m with clear anti Q-slope. The vertical test results are shown in Fig. 6.

The above test results of 3/60 N-doped cavities scatter a bit, with respect to the removal thickness of final EP. High Q_0, larger than 3×10^{10} in the medium field range, appears in the final removal thickness from 10 µm to 15 µm. This indicates the large margin of final EP removal after 3/60 doping. More studies to find the optimum final removal is underway.

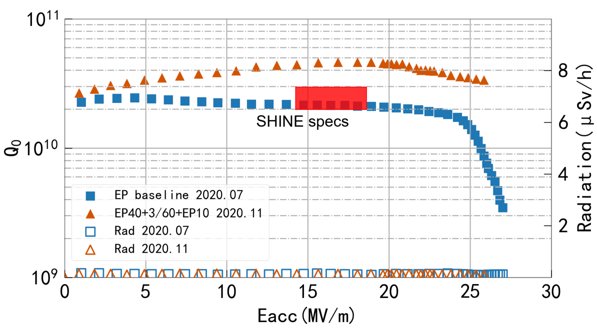

Figure 6: Vertical test results of new FG single-cell cavity NF33.

$$R_s = A\lambda_L^3 \frac{\omega^2 l_e}{T} e^{-\Delta/T}(1 + \frac{\xi_0}{l_e})^{3/2} + R_{res} \qquad (1)$$

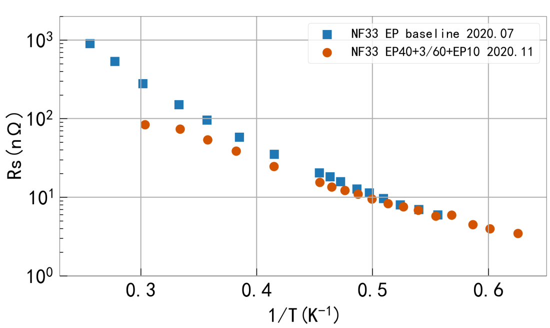

Figure 7: The surface resistance values for the fine-grain cavity NF33.

In order to obtain the surface resistance, we use the least squares method to fit the Q-T curve of cavity NF33 (shown in Fig. 7) with the approximating BCS theory as shown in Eq. (1) at low field (~1.5 MV/m). We find that after EP baseline process, the residual resistance of fine-grain cavity NF33 is about 3.2 nΩ and the BCS resistance at 2K is around 7.6 nΩ. After N-doping, the residual resistance lowers to about 2.5 nΩ, and the BCS resistance is about 7.5 nΩ. In the future, more tests will be done to study the surface resistance versus accelerating field.

FUTURE PLANS

We have constructed a new cavity-treatment platform at Wuxi, China. A new small EP device for single-cell 1.3 GHz cavity is under operation, as shown in Fig. 8. It is able to realize "cold EP" function. In near future, the high-Q studies on both single-cell and 9-cell cavities will be carried out on this new platform.

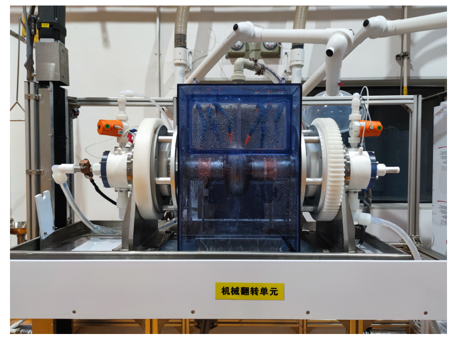

Figure 8: The new small EP device at Wuxi, China.

SUMMARY

After upgrade of cold EP function, the simple EP device can realize good light EP treatment. We have achieved some obvious progress of N-doping results on single-cell cavities, applying 3/60 recipes and "cold EP". On fine-grain single-cell cavity, we achieved $Q_0 = 4.6 \times 10^{10}$ at 16 MV/m and maximum $E_{acc} = 26$ MV/m. More studies for both single-cell and 9-cell cavities with new devices at Wuxi platform are under way.

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