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THE EFFECT OF HELIUM PROCESSING AND PLASMA CLEANING FOR LOW BETA HWR CAVITY*

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Abstract

The commissioning of the 25 MeV high power and high intensity proton Linac demo for CiADS showed that the performance of the SRF cavities was mainly limited by field emission inside the cavities. Therefore, the techniques of helium processing and reactive oxygen plasma cleaning have been developed to mitigate field emission issues. We performed an experiment with a low beta HWR cavity exposed to air directly and processed by helium and reactive oxygen. In this paper, the details of the experiment will be described, the efficiency of helium processing and plasma cleaning will be compared and discussed

INTRODUCTION

The injector II demo facility of the CiADS project has been designed and developed by the institute of modern physics (IMP) and the institute of high energy physics (IHEP) at IMP, Chinese Academy of Sciences, which can provide a maximal proton energy of 25 MeV [1]. Four cryomodules were used in the superconducting accelerating section, which host three types of superconducting cavities (i.e. half wave resonator (HWR) with beta value of 0.10 (HWR010), HWR015 (developed by IMP) and Spoke021 (developed by IHEP). The commissioning of the linac of injector II revealed that the performance of the SRF cavities were mainly limited by field emission effect inside the cavity. We observed the operating gradient degradation of HWR cavity from vertical test to horizontal test, and during the operation process.

The dependence of the field emission electron current on the working function of the material and the surface electric field are depicted by Fowler and Nordheim (FN) equation as following [2],

$$I \propto (\beta_{FN}E)^{2.5}\exp\left(\frac{-B_{FN}\varphi^{3/2}}{\beta_{FN}E}\right)$$

Where β_{FN} is the field enhancement factor related to the surface physical morphology of metal, φ is the working function related to the chemical state of the surface of metal. Therefore, the decrease of β_{FN} and the increase of the φ of the Nb surface is the key mechanism for the mitigation of field emission inside the cavity mainly manufactured by Niobium. In light of this, many efforts have been made in SRF community, the in-situ surface processing methods have been adopted and developed, including RF conditioning, cryogenic helium processing and low-density reactive oxygen plasma processing etc., which has also been adopted and developed for HWR cavities at IMP. The possible mechanism of RF conditioning and helium processing is to modify the physical morphology of the Nb surface [3], thereby, decrease the field enhancement factor β_{FN}. But for the hydrocarbon contaminants observed on the niobium samples processed by standard surface processing procedures [4], the reactive oxygen plasma cleaning is effective, which has been validated on elliptical cavities by the researchers from SNS [5].

Two series of the Helium processing of HWR010 and HWR015 in cryomodule were performed in 2016 and 2017 at IMP [6]. The results showed that the helium processing method can recover the onset of field emission of the cavity experienced the gradient degradation. But can not further increase the onset of the field.

Our previous studies on the Nb samples by XPS and UPS showed that carbon contamination can largely degrease the work function (from 4.4 eV to 3.75 eV), the increase of oxidation state of Nb resulted in the increase of the work function, where the samples were processed by the standard surface processing procedures developed at IMP. Then, the work function were successfully improved by Ar/O2(97%: 2.5%) plasma sustained by a power of 50 watts with the frequency of 13.56 MHz, the physics behind the improvement is the elimination of the carbon contaminants on the sample surface, which was verified by the residual gas analysis data [7]. The plasma inside the HWR015 cavity volume was also successfully ignited, where we optimized the plasma parameters, developed a special plasma controlling method using the power reflecting coefficient. The efficiency were validated by the vertical test, the results showed that the hydrocarbon contaminants on the inner surface of the cavity were removed, and the quenching electrical field was improved by 29% due to the mitigation of field emission effect inside the cavity after Ar/O2 plasma cleaning [8].

For the purpose of further understanding the efficiency of the helium processing and Ar/O2 plasma cleaning methods, in present work, we designed an experiment, performed the helium processing and Ar/O2 plasma cleaning for an HWR015 cavity polluted directly by Air. The results showed that the performance of the cavity can be recovered to the level after experiencing the standard processing procedures.

EXPERIMENTAL SETUP

Figure 1 shows the experimental schematic of air pollution for HWR015 cavity positioned on the vertical test stand. A 0.3-micrometer filter was used between the air container and the cavity, the pressure of the cavity and

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gas pipe system was 9.4 mbar after air pollution. The experimental steps were as follows:

1) Cool down the cavity to 4 K after air pollution with all valves closed and test the cavity at 4 K;

2) Warm up the cavity to room temperature, pump out the air and perform the 120 ^{0}C baking for 58 hours;

3) Cool down the cavity to 4 K and perform the test;

4) Warm up the cavity to room temperature and perform Ar/O2 plasma cleaning;

5) Cool down the cavity to 4 K, and test the cavity;

6) Perform the helium processing for the cavity at 4 K, warm up the cavity to about 30 K, pump out the residual helium gas;

7) Cool down the cavity to 4 K and perform the test;

8) Repeat steps 6 and 7.

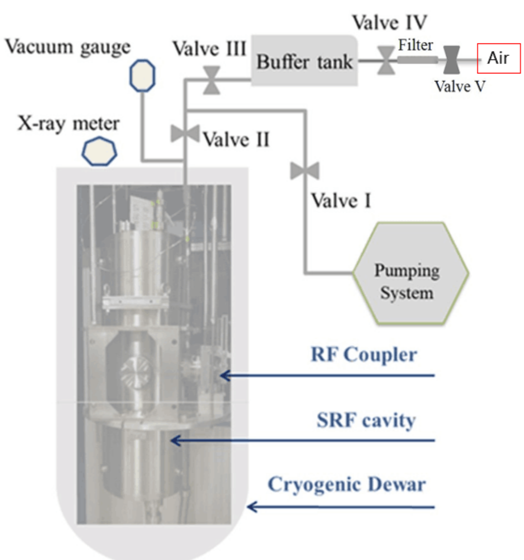

Figure 1: The experimental schematic of air pollution for HWR015 cavity.

RESULTS AND DISCUSSION

Figure 2 and 3 gives the test results at 4 K in each step mentioned above. In experimental step 2, the cavity was polluted the by air with a pressure of 9.4 mbar at room temperature and a pressure of 5.0E-6 Pa at 4 K. The field inside the cavity cannot be established with 8 hours RF pulse conditioning. Then, the cavity undergone 120 ^{0}C baking for 58 hours, the curve (a) in Fig. 2 gives the test results at 4 K with 6 hours RF pulse conditioning (step 3), the performance of the cavity is limited by MP effect.

In experimental step 4, the cavity was processed by Ar/O2 plasma, where the pulse plasma was used (pulse on/off (10-30s)/(2-5mins)), with a total active plasma cleaning time of 150 mins, a pressure of 0.5-0.8 Pa, and an RF power of 60-80 watts to sustain the plasma. As one can see, the low field Q0 was recovered to 5.0E9, again encountered the MP effect (see Fig. 2 and 3 curve (b)). The low field MP disappeared after 5 mins RF conditioning at just before quenching field (see Fig. 2 and 3 curve (c)), but the MP at 17 MV/m was encountered, which is accordance with the MP simulation results of the HWR015 cavity reported in reference [9], the MP barrier for this cavity is between 16 MV/m and 19 MV/m of the peak surface electrical field. Finally, the cavity quenched at 41.8 MV/m after sustaining extra RF conditioning at just before quenching field described in curve(c) in Fig. 2 (see Fig. 2 and 3 curve (d)), and the performed of the cavity was limited by field emission.

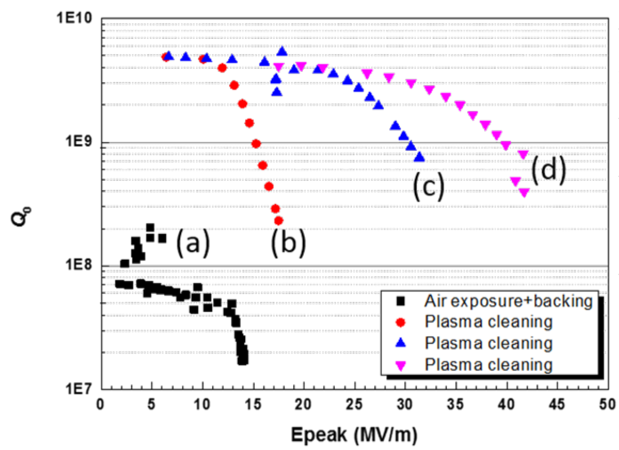

Figure 2: The Q0 vs Epeak test results of the HWR015 cavity experienced air exposure and baking (curve (a)) and plasma cleaning (curve (b), (c), (d)).

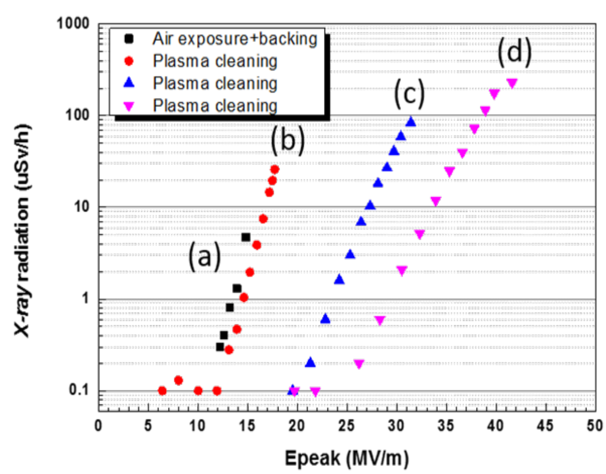

Figure 3: The X-ray test results of the HWR015 cavity experienced air exposure and baking (curve (a)) and plasma cleaning (curve (b), (c), (d)).

The possible mechanism of the results depicted in Fig.2 and Fig. 3, can be explained as following; Since the cavity was polluted by Air, both the hydrocarbon contaminants and the particulate contaminants might be introduced. As mentioned before, the Ar/O0 plasma can eliminate the hydrocarbon contaminants. When the cavity was cleaned by Ar/O0 plasma, the volatile by-products of the reaction between reactive oxygen group and the hydrocarbon contaminants was produced, pumped out of the cavity, and judged using residual gas analysis during plasma cleaning process. Therefore, we believed that the performance of the cavity limited by the hydrocarbon contaminants was improved after plasma cleaning. RF

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conditioning might modify the surface physical morphology, therefore lower the field enhancement factor β_{FN} to some extent.

For further improve the performance of the cavity, we performed the helium processing for the cavity at just before quenching field depicted in the curve (d) of Fig. 2, and at two different pressures of 1.2E-3 Pa and 4.1E-3 Pa. The performance of the cavity was recovered to the standard level as shown in Fig. 4, where the cavity was processed by the standard surface processing procedures. The reason behind the performance recovery might be that the field enhancement factor β_{FN} was further lowered by helium processing.

In light of the results obtained in our experiments, we conclude that the performance of the cavity polluted by air can be recovered with the combination of plasma cleaning, RF conditioning and helium processing.

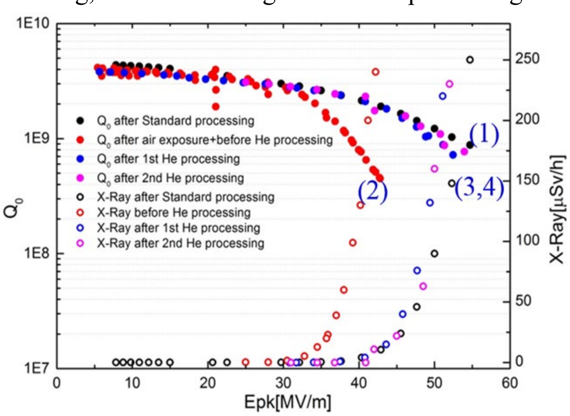

Figure 4: The test results of the HWR015 cavity, after standard surface processing (curve (1), black circles); after air exposure, baking(120^{0}C for 58 hours), and Ar/O2 plasma cleaning (curve (2), red circles); after helium processing (curve (3,4), blue and pink circles).

CONCLUSION

The limiting factor of the HWR cavity for obtaining higher accelerating gradient is the field emission effect, which was revealed by the commissioning of 25 MeV proton linac demo for CiADS at IMP. The helium processing, and Ar/O2 plasma cleaning methods have been adopted and developed to mitigate the field emission effect inside the HWR cavity.

In this paper, we reported that the performance of the HWR cavity polluted directly by air, can be recovered when the cavity were processed by using the Ar/O2 plasma cleaning, RF conditioning and helium processing methods together. This work can provide a technical solution for the performance recovery of the SC cavity in CM polluted directly by Air.

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