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VERTICAL TEST RESULTS OF PLASMA IN-SITU CLEANING ON LOW BETA HWR CAVITY*

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Abstract

Field emission occurred in SRF cavity is the major limitation to operate at high gradient with stability. The plasma in-situ cleaning for the low beta HWR cavity was carried out to remove the hydrocarbons contaminants on the inner cavity surface. And the vertical test results indicated that the field emission effect was relieved with the increasing of the quench point and emission set-on point. Thus, oxygen active plasma processing can be an effective method to solve the field emission issues for the low beta HWR cavity.

INTRODUCTION

The Chinese-Accelerator Driven System (C-ADS) has been developing for the treatment of the nuclear wastes at Institute of Modern Physics, Chinese Academy of Sciences. A 25 MeV superconducting proton linac injector has been constructed, and it had been commissioned successfully for the continuous wave proton beams with the current of 170 μA. However, the operation stability of this linac was limited by the trips of the HWR cavities caused by field emission. In order to mitigate the field emission issues in the HWR cavities, the in-situ plasma cleaning technique was proposed at IMP.

For removing the hydrocarbon contaminants covered on the inner surface of the cavity, the inert gas argon was used for the plasma ignition and a few percentage of oxygen gas was mixed as oxidant [1-6].To understand the plasma interaction with niobium surface during the plasma cleaning progress, the characteristics of electron temperature, free electron number density and the vertical test results of HWR cavity by plasma cleaning are presented in this paper.

PLASMA EGNITION IN HWR CAVITY

RF plasma discharge experimental platform for the in-situ plasma cleaning is shown in Fig. 1. It consists of RF system, vacuum system and the optical emission spectrum (OES) system and mass spectrometer.

An HWR015 was used for the plasma discharge experimental study offline. HWR15 was optimized for accelerating protons with a relative speed of light at 0.15, and the fundamental eigen frequency is 162.5 MHz. In order to obtain the similar conditions in cryomodule for HWR015 cavity, the fundamental power coupler (FPC) with dual ceramic windows structure was installed for the cavity, as shown in the Fig. 1.

The Argon and oxygen mixed plasma was ignited in the HWR015, and the glow brightness in three directions at different pressures and oxygen volume ratios is illustrated in Fig. 2. The lower gas pressure and the smaller oxygen volume ratio has the stronger luminance of the plasma light and more uniform distribution of discharge will be achieved in the cavity.

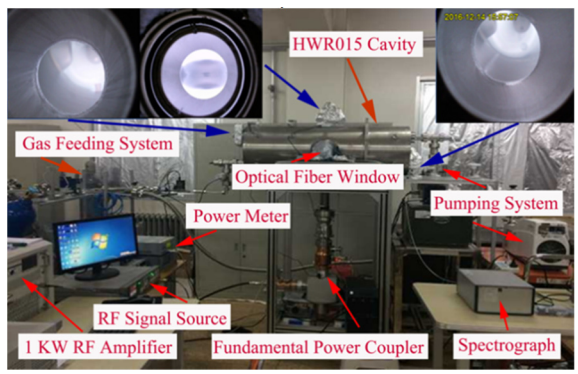

Figure 1: The experimental platform of RF plasma discharge for HWR015 cavity.

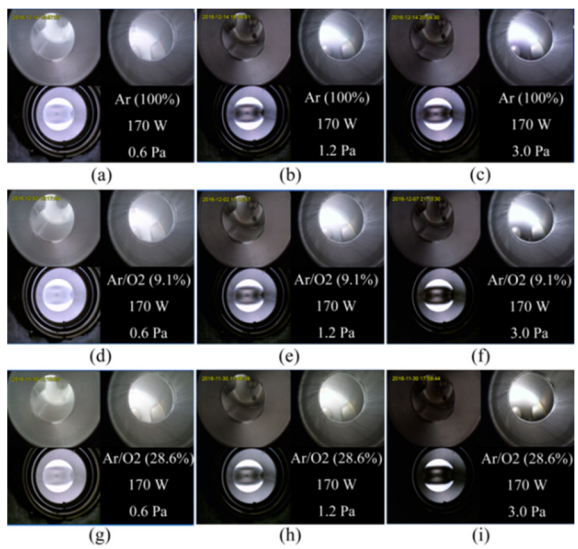

Figure 2: Brightness of the plasma discharge in the HWR015 cavity, at different gas pressures and oxygen volume ratios. The top two cameras were fixed at the two ends of the cavity and the bottom left one was installed at the middle of the cavity.

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Figure 2 indicated that the plasma was concentrated in the middle of cavity, but thin in the both end sides of cavity. This because that the standing wave in the HWR cavity is in the transverse electric and magnetic field mode, which divides the EM field into a strong electric field region at the middle of the cavity and two strong magnetic field regions at the both ends of the cavity [7-8]. This non-uniform electric field distribution leads to the plasma concentrated at the middle of the cavity, because the electric field heats the plasma in this region, from where the seed electrons are mainly produced. Then the above seed electrons are transferred to the both ends of the cavity by drift and diffusion to ignite the plasma discharge in this region.

PLASMA PARAMETERS FROM OES

The optical emission spectroscopy (OES) based technique is a non-invasive method for diagnosing free electron number density, electron temperature and active species in the plasma region by measuring the relative intensity of the emission lines [9-11]. Based on the LET model and the corona model, eleven spectral lines of the argon atom were chosen at the wavelength of 687.1, 693.8, 696.5, 703.0, 706.7, 714.7, 720.7, 731.2, 750.4, 751.5 and 763.5 nm to evaluate the electron temperature, as shown in Fig. 3. The electron temperature decreases between 1.2 eV and 2.2 eV as the increasing of the gas pressure, this matches well from literature with an average 2eV for gas plasma discharges [12].

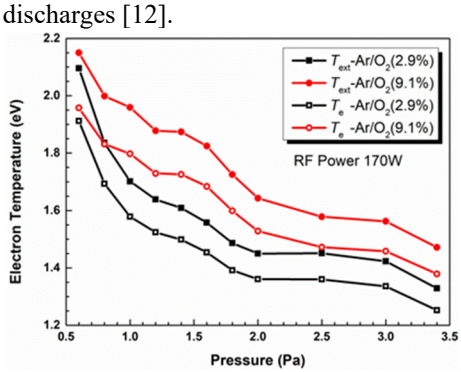

Figure 3: The dependence of the electron temperature on the gas pressure.

The Saha-Boltzmann equation was used to estimate the electron density by using the optical intensity ratio of the argon atomic and ionic lines [13-14]. In this study, the emission lines of the atom at 451.1nm and the ion at 476.5 nm were used to calculate the electron density.

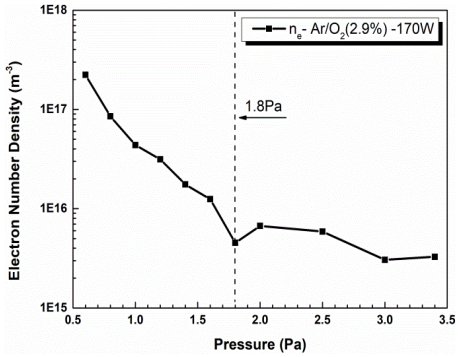

Figure 4: Electron number density as function of the gas pressure.

Figure 4 depicts the electron number density as a function of the gas pressure on the condition of the oxygen volume ratio at 2.9% and RF power at 170 W. As one can see, when the gas pressure is varied from 0.5 Pa to 1.8 Pa, the n_e decreases rapidly from 2.2×10^{17} to 4.5×10^{15} m^{-3}. For gas pressure above 2.0 Pa, the n_e is stable at about 5.0×10^{15} m^{-3}.

PLASMA IN-SITU CLEANING AND CRYOGENIC TEST OF THE HWR CAVITY

Experiment Procedure for Plasma Cleaning on Vertical Test Stand

Following the above experiments of the plasma ignition and characterization, the inner surface of the HWR015 cavity was etched by a light buffered chemical polishing (BCP) with about 21 um material removal, to remove the possible oxidation layers coated on the niobium surface, which caused by the long-time plasma discharge inside the cavity. In order to meet the requirements of the cryogenic test at 4 K and plasma ignition at room temperature, an adjustable coupler (AC) was designed and assembled instead of the FPC. The Qext of AC can be adjusted from 1.0×10^4 to 5.0×10^9. And the experimental setup is identical with the one in Fig. 2 but without the FPC. The procedure is as follows:

(1) Test the cavity at 4 K as baseline after the standard surface treatments, including the BCP, the high pressure rinsing (HPR) by deionized water and the vacuum baking at 120 centigrade for 48 hours.

(2) Process the cavity with reactive oxygen plasma at room temperature to remove the hydrocarbon contaminants.

(3) Test the cavity at 4 K again to verify the effect of the plasma cleaning.

Chemical Reaction and Byproducts During Plasma Cleaning

During the process of in-situ plasma cleaning of the HWR015 cavity, the Q_{ext} of the coupler was set at 1.1×10^4. The oxygen volume ratio was set in the range from 3% to 10%, the gas pressure was between 0.6 Pa and 1.2 Pa, and the RF forward power between 80 and 120 W was used. To avoid the significant heat depositing on the

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inner surface of the cavity during the plasma cleaning process, a short plasma pulse was used, which has a width between 5 and 15 seconds, the interval time of each pulse was set between 1 and 3 minutes. The total active plasma processing time was about 95 minutes over 28 hours.

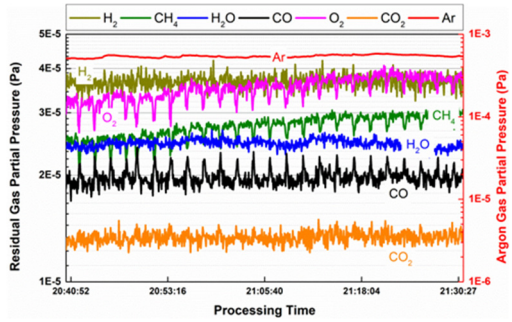

Figure 5: Parts of the RGA data obtained during the plasma processing of the HWR015 cavity.

A quadrupole mass spectrometer (QMS) was used as the residual gas analyser (RGA) to monitor the gas pumped out from the cavity during the plasma in-situ cleaning process. Parts of the RGA data for some selected gas are shown in Fig. 5. The distinctive peaks of each curve correspond to each short plasma pulse. The downward peaks of the oxygen indicate that the oxygen was consumed as the oxidant for the chemical reaction during the plasma cleaning process. The methane, which is one type of the hydrocarbon contaminants of the SRF cavity [1-5], was degraded. Meanwhile, the gas of H_2O, CO and CO_2 were also measured, which are the volatile byproducts of the chemical sputtering of hydrocarbons by the oxygen reactive plasma. Particularly, the obvious peaks of CO indicate that CO is the major component of the volatile byproducts.

Performance of the HWR Cavity Improved by Plasma In-situ Cleaning

The cryogenic test results of the HWR015 cavity are shown in Fig. 6, it indicates that the performance of the cavity can be significantly improved by plasma in-situ cleaning. The maximal peak surface electric field E_{peak}, which relates to the maximal available accelerating gradient, was increased from 54.8 MV/m to 70.3 MV/m. The onset of the X- ray radiation that caused by the bremsstrahlung of the field emitted electrons was raised from 32.1 MV/m to 59.5 M/m, and its maximal dose was decreased from 250.8 μSv/h to 4.5μSv/h. Before the plasma cleaning, the performance of the cavity was limited by the field emission, which induced the Q_0-slope between 43.1 MV/m and 54.8 MV/m, and the cavity finally quenched at 54.8 MV/m by the overheating. After the plasma cleaning, the field emission effect was removed completely until the E_{peak} approaching 59.5 MV/m. Therefore, the oxygen reactive plasma in-situ cleaning is an effective method to improve the performance of the HWR cavity by mitigating the field emission effect.

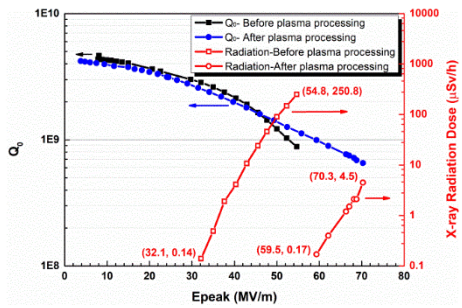

Figure 6: Vertical test results of an HWR015 cavity processed by the standard surface treatments and plasma.

CONCLUSION

The reactive oxygen plasma can be ignited in the HWR cavity. The plasma parameters were diagnosed by the optical emission spectra method. The electron number density and free electron temperature decreases as the increase of the total gas pressure, and the dissociated oxygen atom intensity decreases as the increase of the gas pressure but increases with the increasing oxygen volume ratio. In light of the knowledge learned from the studies of the plasma ignition and characterization, the in-situ plasma cleaning was applied to an HWR cavity with an adjustable coupler for vertical test at 4 K. The RGA data taken from the cavity during the plasma cleaning process revealed that the hydrocarbon contaminants were removed from the inner surface of the cavity. And the vertical test results indicate that the plasma in-situ cleaning is an effective technique to mitigate the field emission effect of the HWR cavity, therefore improve the accelerating gradient significantly. The plasma in-situ cleaning of the cavity in the horizontal test cryomodule will be implemented in our next work.

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