DEVELOPMENT OF PLASMA CLEANING TECHNOLOGY AT CORNELL UNIVERSITY*

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Abstract

Cornell University is developing the plasma cleaning technology as an alternative cleaning technique for SRF cavity surface preparation. In experiments, we successfully ignited the plasma in a single-cell SRF cavity. However the experiments were limited by the peak electric-fields in the RF coupler. In this paper, we show the analysis of the limitation and propose a new design of the coupler which can eliminate the limitation.

INTRODUCTION

Plasma cleaning is a well-known technology of removing impurities and contaminants from surfaces. Plasma can be generated in a container filled with gases such as argon, nitrogen etc., by applying high frequency voltages, typically from kHz to GHz. The ionized atoms of the gases can hit the surfaces and remove the contaminants. The application of plasma cleaning technologies to Superconducting radio frequency (SRF) fields can be quite successful. It has been reported by Oak Ridge National Laboratory that the performance of an offline cryomodules had been improved after plasma processing without the cryomodule disassembled [1]. This in-situ plasma processing can effectively reduce field emission which was caused by particles on the cavity surfaces in the cryomodule.

One of the known technical challenges of plasma cleaning for SRF applications is to generate plasma in cavity cells, but not in RF-coupler sections or cavity beam pipes. This is because the gas for plasma ignition will fill the entire volumes of the cavity and coupler. The plasma is generated in the strongest electric-field region with an appropriate gas pressure. Hence, it requires that the strength of electric-fields in the coupler sections be less than in the cavity in which the iris has the peak electric-fields. Otherwise, the plasma generated in the coupler will react with its antenna which is typically made out of copper. The copper can be delivered to and coated on cavity surfaces by the plasma.

At Cornell University, we are developing plasma technology for 1) cleaning SRF cavity surfaces to reduce field emission; and 2) removing bad oxides from cavity surfaces to improve medium field quality factors (Q_0) of SRF cavities. The potential application of this study can be performance improvement of the Cornell main linac prototype cryomodule [2]. In this paper, we present the latest progress of plasma works at Cornell University.

THE LIMITATION OF CURRENT COUPLER SET-UP

The reference [3] presents our previous work; we successfully ignited plasma in a 1.3GHz single-cell TESLA-shape SRF cavity. The schematic of the set-up is shown in Figure 1, in which the coupler is connected to one end of the cavity; the DC magnetic field, whose direction is perpendicular to the electric-fields, is applied only in the cavity-cell region by an external dipole magnet; the view-port is installed on the other end of the cavity. Observing from the view port, an example image is shown in Figure 1 (up-right subplot) showing where the plasma is produced inside the cavity set-up.

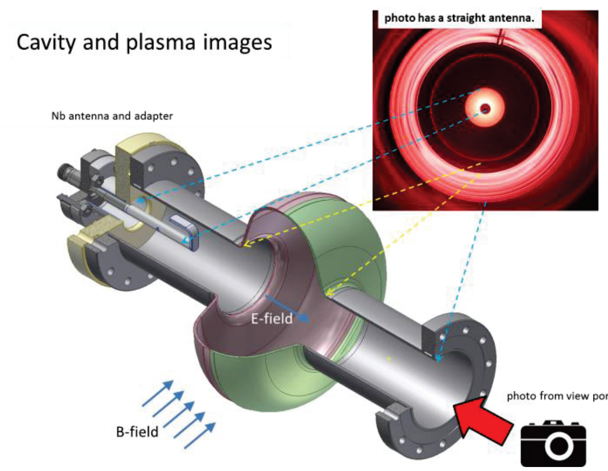

Figure 1: The schematic of plasma cleaning set-up. The up-right subplot shows an image observed from the view port.

The plasma ignition of a gas relates to three factors: gas pressures, RF-powers (or peak electric-fields), and DC magnetic fields. In our case, the ideal gas pressure is in the range of 15-100mTorr for argon [4]. In principle, higher pressure is better because the plasma has higher density; hence it can give better results of cleaning. However the higher pressure decreases the threshold of gas discharge predicted by Paschen's law [5], i.e. a high pressure gas can be discharged by a low electric-field and vice versa. Figure 2 shows the simulation of the electric-field distributions in the cavity and coupler. The strong electric-fields (displayed by the red colours in Figure 2) occur in the feedthrough and adaptor sections. It indicates that the plasma can be generated in the coupler easier than in the cavity, which is not for our purposes and can cause cavity damage.

The DC magnetic-field can extend the lifetime of electrons, thus it can generate the electron cyclotron resonance (ECR) plasma even at low pressures [6]. We applied the magnetic-fields in the cavity section; and successfully generated the plasma at 0.1mTorr in the cavity; but suppressed it in the coupler. In the experiments, we used 500Gauss permanent magnets for the 1.3GHz ECR

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plasma. The RF-power in our study was 100-120W which can establish ~30-32kV/m fields in the cavity.

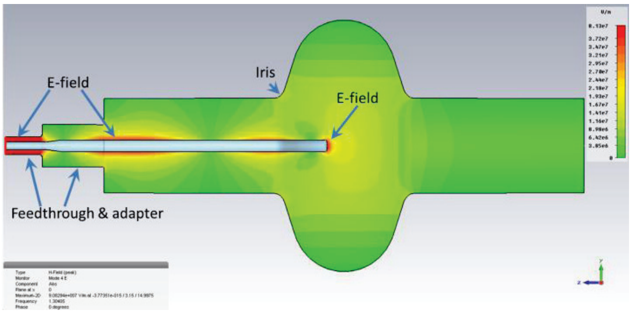

Figure 2: The Simulation of electric-field distribution of a 1.3GHz single-cell SRF cavity with a coupler.

Figure 3 a)-d) are the summary of the plasma observed under different conditions when the cavity were filled with argon gas. Figure 3 a) shows the plasma concentrated in the feedthrough indicated by the bright centre and the dark beam pipe, when the pressure was at the range of 15-100mTorr; but the plasma was also sometimes switched into the beam pipe due to the peak electric-fields in it, which is shown in Figure 3 b). When the pressure was decreased to 0.1mTorr, the plasma was ignited in the cavity cell region which is displayed in Figure 3 c). In addition, measured temperature increases on the exterior wall of the cavity indicate the plasma location as well. The plasma can locally heat the cavity up to ~60-70°C. The plasma density is related to the fluxes of the magnetic-field. In the experiment, we increased the flux density in the upper region of the cavity depicted by Figure 3 d). It shows that the strongest magnetic-field region has the brightest plasma which suggests it has the highest energy.

The limitation of the current set-up is that we cannot increase the plasma energy further; because if we increased RF-power, the electric-fields in the coupler would exceed the threshold again even at the low pressure, which would cause the plasma ignition in coupler. This requires that we have to decrease the gas pressure further to suppress the plasma in coupler, but the total energy of the plasma would not be improved at all. In addition, the RF amplifier for the experiments can provide 200W at maximum as well as the RF cables and feedthrough cannot work at 200W for long time. Hence there is not much room to increase RF power. Since the dipole magnet in the experiment is a permanent magnet, we cannot dramatically tune the flux as well. Therefore the solution to overcome the limitation is to design a new RF coupler to eliminate the peak electric-field in it.

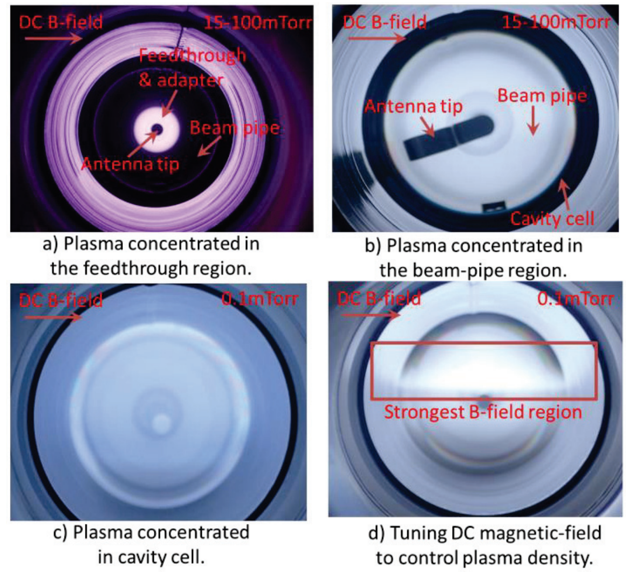

Figure 3: The summary of observed plasma ignited at different conditions.

THE NEW DESIGN OF THE COUPLER

The cause of the current limitation is the outer conductor that has a suddenly decreased from the beam pipe to the feedthrough at the adaptor. The two steps shown in Figure 2 dramatically enhanced the electric-fields locally. Hence the new design of the coupler should have a smoother transition between the cavity and coupler. We adopt the Cornell ERL injector coupler [8] which is able to handle up to 75 kW CW RF power. In the design which is depicted in Figure 4 a) and b), the diameter of the coupler outer-conductor is 60mm which is very close to the beam pipe diameter 78mm. A port adaptor has been designed to connect them together. The small changes in the diameters will not trigger electric-field enhancement in the coupler. A niobium antenna extension has been added to match the cavity material, as is displayed in Figure 4 c).

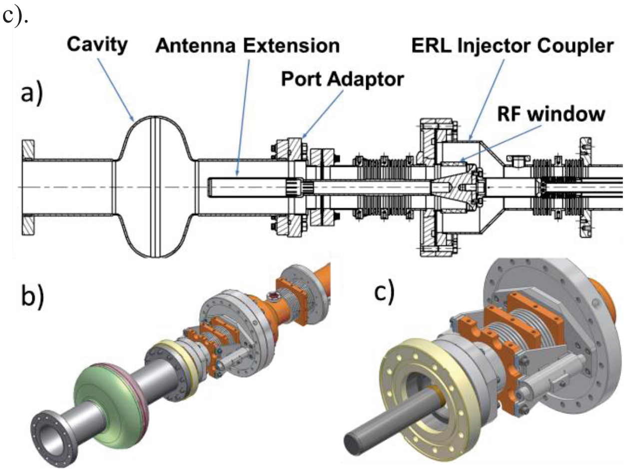

Figure 4: The new design of the coupler and cavity: a) 2D drawing of the coupler design connected to the cavity; b) 3D model of the coupler design; c) The details of the antenna extension of the coupler.

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A simulation of the electric-field distribution has been carried out to check the peak electric-fields in the coupler. We calculate the ratio of the peak electric-fields in the coupler and the peak electric-field in the cavity to satisfy the requirement, i.e. $E_{coupler}/E_{cavity} \ll 1$. The result of the ratio versus the antenna insert depth (denoted as L_a in Figure 5) is shown in Figure 5. Here we checked two peak electric-fields in the coupler: one is the field the at the antenna tip depicted by the red curve in Figure 5; the other is the maximum field in the coax section which is the blue curve. The green curve in Figure 5 is the external Q of the coupler versus the insert depth.

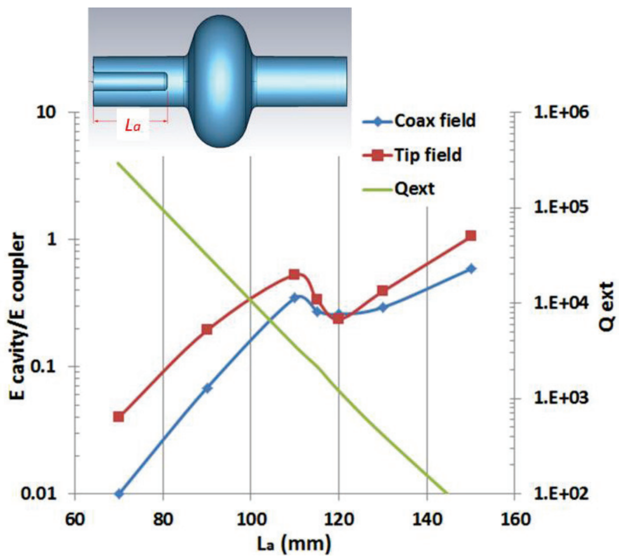

Figure 5: The curves of the ratio $E_{coupler}/E_{cavity}$ versus insert depth L_a as well as the external Q versus L_a.

To determine the best insert depth of antenna, it needs to minimize the electric-field ratio as well as match the cavity loaded Q_L expressed in Eq. (1),

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{plasma}}. \tag{1}$$

Typically, the Q_0 of a niobium cavity is about 8000 at room temperature. But it's difficult to estimate the plasma quality factor (Q_{plasma}) precisely; what can be known from Eq. (1) is $Q_L \leq Q_0$. Thereby we assume Q_L is in the range of 2000-8000. The simulation shown in Figure 5 implies when the insert depth is equal to 80 and 120mm, it has relatively low ratios, 0.25 and <0.1 respectively. The external quality factors of the two points are 1×10^5 for 80mm and 1×10^3 for 120mm. According to Paschen's law, 20-40kV/m is needed for the argon gas discharge at the pressure 15-100mTorr. Despite that the higher Q_e (1×10^5) requires more RF input power to establish the electric-fields in the cavity, $L_a = 80$mm is better because of the lower field ratio (<0.1). Figure 6 displays the calculation of the peak electric-field (E_p) versus the input power at different Q_L. Even in the worst case $Q_L = 2000$, $Q_e = 1 \times 10^5$, 600W can establish 40kV/m in the cavity. In the new set-up, we plan to use a 1.3GHz 5kW solid state amplifier [9] which allows us to input 100-2000W in the cavity.

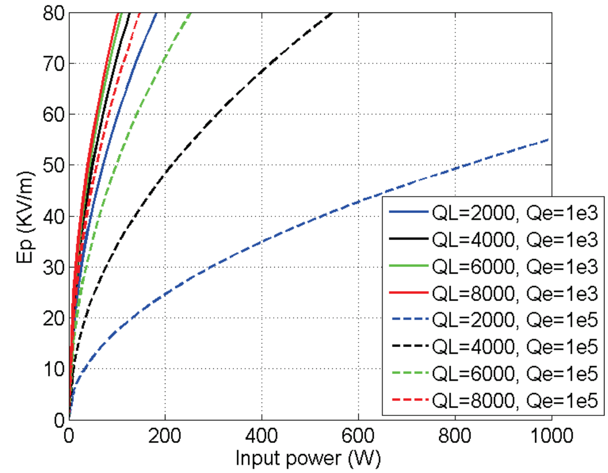

Figure 6: The peak electric-fields versus the input power at different Q_L and Q_e.

CONCLUSION

We generated plasma in a single-cell cavity. The limitation of our experiment is the peak electric-fields in the coupler. A new design of the coupler has been proposed. When the insert depth of the antenna is 80mm, the ratio is less than 0.1 which suggests the field in the coupler is much smaller than in the cavity. In addition, the maximum needed input power is 600W, which can be provided by the new solid state amplifier.

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