ECR PLASMA CLEANING: AN IN-SITU PROCESSING TECHNIQUE FOR RF CAVITIES*

G. Wu#, H. Jiang, T. Khabiboulline, I. Pechenezhskiy, T. Koeth, J. Reid, W. Muranyi, B. Tennis, E. Harms, Y. Terechkine, H. Edwards, D. Mitchell, A. Rowe, C. Boffo, C. Cooper, L. Cooley, R. Schuessler, Fermilab, Batavia, IL 60510, U.S.A.
W-D. Moeller, DESY, Hamburg, Germany
C. Antoine, CEA/Saclay, France
A. Romanenko, Cornell University, Ithaca, NY 14850, U.S.A.

Abstract

A condition for Electron Cyclotron Resonance (ECR) can be established inside a fully assembled RF cavity without the need for removing high-power couplers. As such, plasma generated by this process can be used as a final cleaning step, or as an alternative cleaning step in place of other techniques. We will describe the current effort to study plasma cleaning by ECR in a 3.9GHz cavity.

INTRUDUCTION

The present cleaning regimen for superconducting RF (SRF) cavities involves the use of dangerous concentrated acids for cleaning the internal surfaces. Alternative cleaning processes that avoid the use of acids while still obtaining good results would be highly desirable from a safety point of view. One such process is plasma cleaning, in which surface material is removed via plasma-enhanced chemical reactions and simple ion bombardment. While direct ion bombardment generally does not efficiently remove all contamination, addition of reactant gases allows surface material to form gaseous compounds that can be exhausted through the vacuum system. Glow discharge (DC discharge or RF discharge), magnetron plasma and ECR plasma are among the common techniques applied widely in applications with metal surfaces, as described in [1,2]. Along these lines, glow discharges of H_2, Ar or Ar/O mixtures have been extensively studied for storage ring vacuum vessel cleaning [3]. N_2 RF plasma was successfully used to reduce the water vapor and other contaminants in a megawatt gyrotron RF source [4].

The main debris in niobium SRF cavities includes dust, grease, and other environmental contaminants; flakes introduced from screw threads and other tooling; sulfur particles left behind from electropolishing; and material extending from scrapes and scratches of the cavity surface itself. Ion bombardment via excitation of noble gas or nitrogen can be used to ablate such particles. Chemically reactive plasmas are effective when they attack the base niobium, oxides, hydrocarbons, and sulfur. Reactive gas choices here vary: oxygen can break down hydrocarbon contaminants effectively, while hydrogen effectively breaks down oxides and sulfur. Niobium can be etched by introduction of halogens or oxygen, such as via a mixture of CF_4 and oxygen in Ar carrier gas [5,6]. If the cavity temperature can be elevated, chlorine or bromine can be used to attack niobium also. Recent work at Thomas Jefferson National Accelerator Facility (JLab) and Old Dominion University [7] has explored plasma etching based on earlier niobium etching studies. Similar efforts of surface cleaning in RF systems using plasma are pursued at INFN/Lagnero [8].

ECR PLASMA AND RF CAVITY

A central difficulty in the above plasma cleaning techniques is the need to attach specialized fittings to introduce a plasma-generating device (e.g. a magnetron). This means that there is a risk for re-contamination during the disassembly of the hardware after plasma cleaning and during the subsequent step of attaching RF couplers to the cavity. We propose to remove this risk by generating plasmas inside cavities that are fitted with high-power input couplers and otherwise completely sealed against sources of re-contamination.

If a strong magnetic field is applied to an operating cavity, such that the electron cyclotron resonance frequency in niobium is equal to the cavity resonance condition, plasma generation will result. A schematic of such a setup is shown in Fig. 1. The required field for 3.9 GHz cavities, for instance, is approximately 1400 Gauss. This condition applies as long as injected electrons can stimulate electron emission from the niobium surface, which takes place over a wide range partial pressure of

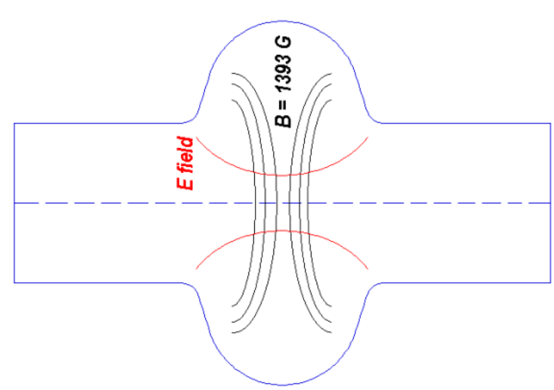

Figure 1: A simple illustration of a 3.9 GHz RF cavity with external dipole magnetic field of 1393 Gauss in the center to form the ECR condition.

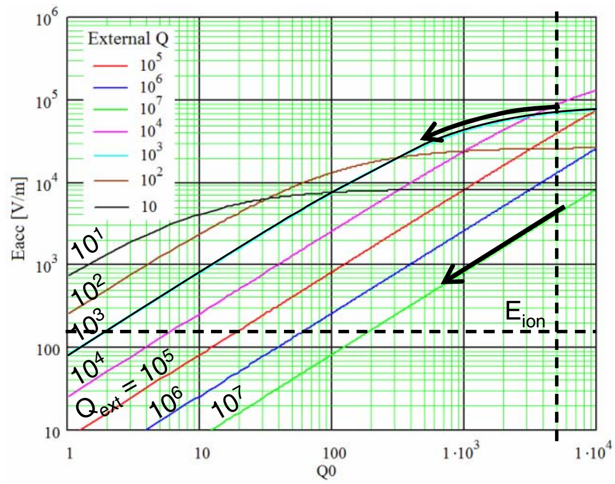

Figure 2. Curves represent the cavity electric field (E_{acc}) for our applied RF input power of 50 W using different values for the input coupling. For the cavity tested, Q_0 = 5000 at 300 K. This is enough to establish ionization of electrons and surface cleaning (denoted by the threshold E_{ion} ~130 V/m) when directly connected to the klystron (input coupling ~10^3). Since Q decays when plasma is established in the cavity, E_{acc} also decays as indicated by the arrows. Still, E_{acc} remains above the electron ionization potential of ~130 V even when high power couplers are used (input coupling ~10^7).

of a convenient solenoid magnet. To satisfy the ECR condition, the magnetic field strength increases in proportion to the RF frequency of a given mode. For now, we focus on the TM_{010} mode, which has strong electric field at the iris and should be effective to mitigate the field emission problem.

EXPERIMENTAL SETUP

Our first attempt to achieve ECR plasmas used a setup shown in Figure 3. The cavity was connected to RF power through a beam pipe coupler commonly used during cavity vertical testing. The coupler has external Q of about 1000. This reduced the power requirement for RF amplifier for initial test as described in Fig. 2. Directional coupler was inserted into the transmission line and a power meter measured incident and reflected power. The RF power was provided by a 120 W traveling wave tube amplifier. The pickup probe for the cavity was optional. The cavity was connected to inlet gas line at the RF input side. A needle valve was installed in the inlet gas line to provide fine adjustment of cavity gas pressure between 10^{-3} Torr and 10^{-6} Torr. A pump station was connected at the other side of the cavity. Two fixed valves were attached to the cavity for future cold test. Initially, cavity was evacuated to better than 10^{-7} torr. A dipole magnet provides the relatively uniform external magnetic field perpendicular to the axis of the cavity. Center field of the magnet was calibrated as a function of current. For a 3.9 GHz cavity, the required magnetic field is 1393 Gauss.

PLASMA TEST

At first, argon was introduced to understand the relationship between plasma power absorption, gas pressure, magnetic field strength and RF frequencies. Plasma light can be seen through view port as shown in Figure 4. The argon plasma could be initiated at various conditions, verifying the flexibility that was hoped for. Once the plasma was excited, it becomes self sustaining at a broad range of conditions as shown in Figure 5.

As plasma absorbed the RF power, the loaded Q reduced to below 1000. This made the bandwidth of RF resonance relatively large. Still, plasma could be sustained within a frequency range as wide as 40 MHz. This allowed us to insert the sample further to the iris of the cavity and still have sustained plasma. The pressure range for stable plasma was also very large, which could provide future opportunity to tune the plasma ion density and ion energy.

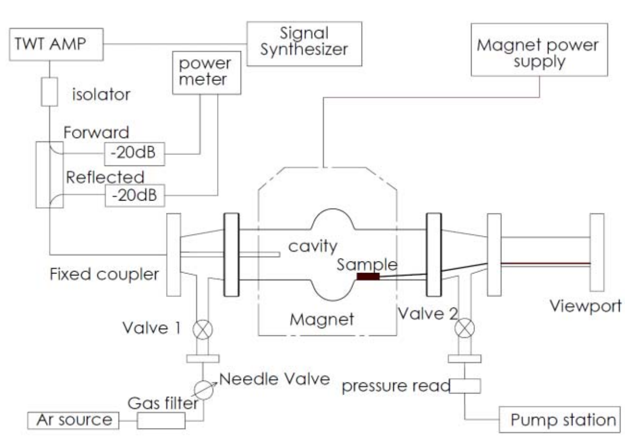

Figure 3: Schematics of plasma excitation in a cavity and sample placement.

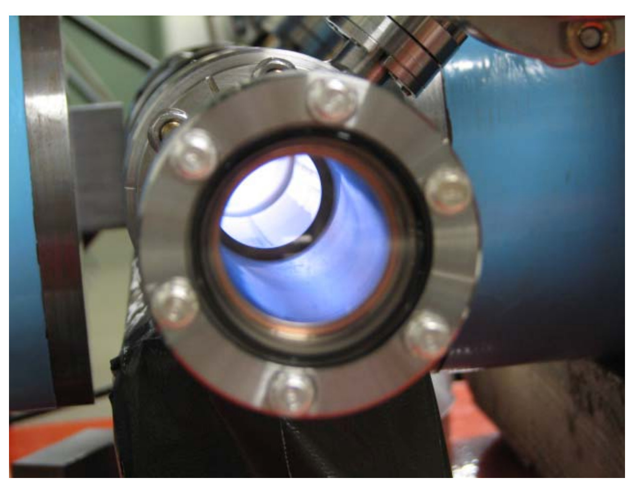

Figure 4. Light of Argon plasma through cavity view port

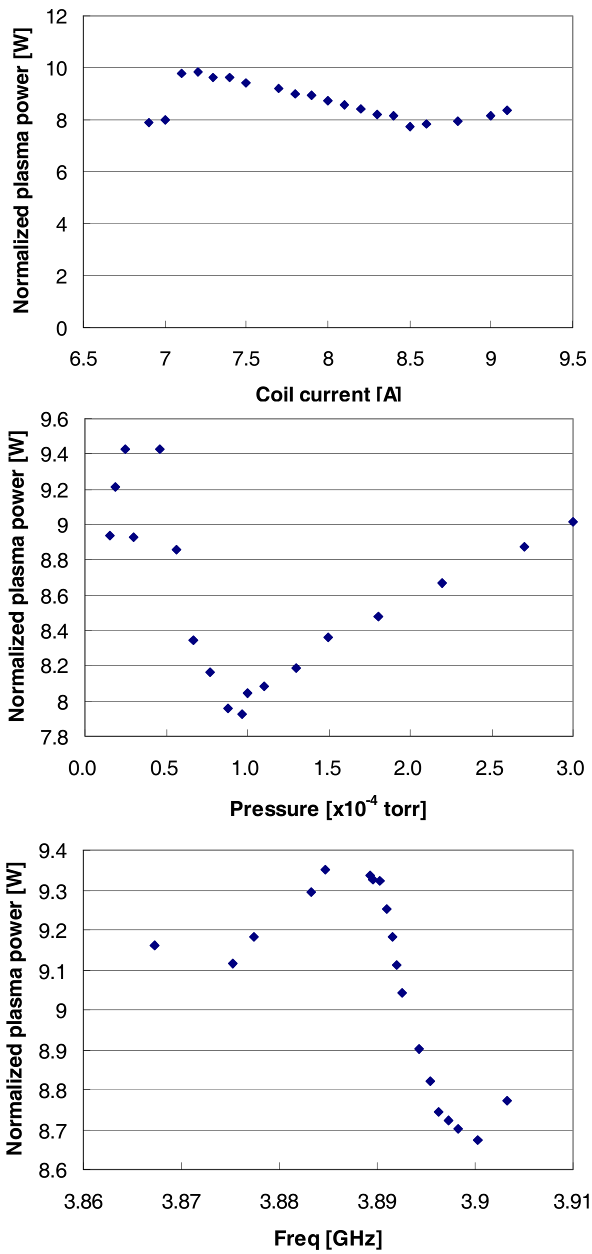

Figure 5. The normalized plasma power absorption at 10 W RF input power; top: Ar pressure 1.0x10^{-4} Torr; middle: Ar pressure 1.0x10^{-4} Torr and Coil current 8.5 A; bottom: Ar pressure 4.4x10^{-4} Torr and coil current 8.6 A

SAMPLE TEST

A purposely contaminated niobium sample was prepared using sulfur powder and its initial condition was characterized by scanning electron microscopy (SEM). Some other contaminants such as carbon are also present. The sample was inserted into the beam pipe near iris of the cavity in Figure 3 and a plasma was initiated. Low density argon plasma was introduced into the cavity to promote gas adsorption. Duration of this stage was 20 minutes. Then a filtered air flow was introduced into the

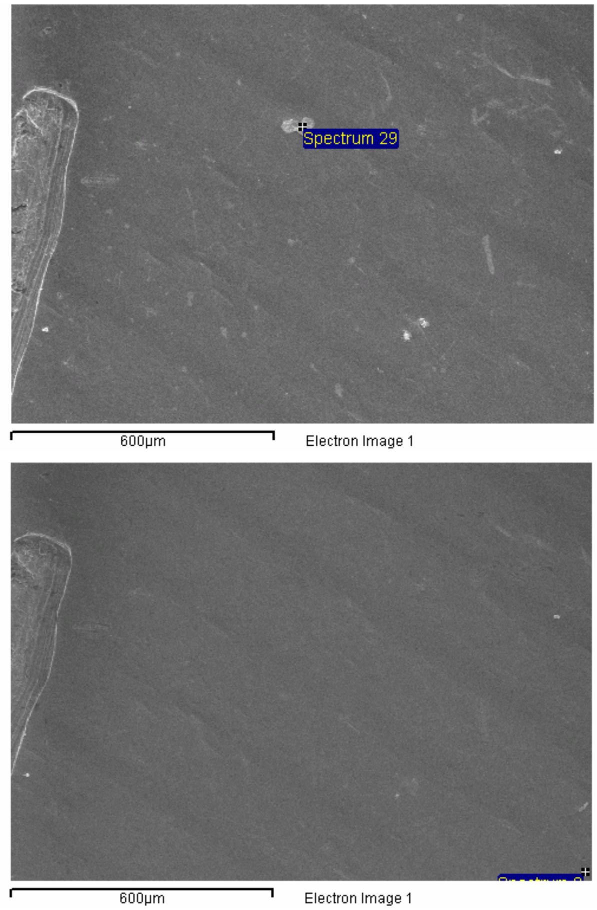

Figure 7. SEM surface images for a niobium sample contaminated by sulfur; left: before plasma treatment; right: after plasma treatment

cavity. A needle valve controlled the air flow so the actual pressure was maintained at ~2.5x10^{-4} Torr. RF power was increased to around 50 W. The air plasma lasted 30 minutes. After this, the sample was taken out to the SEM protected in clean container. Dramatic result of the surface cleaning can be seen from Figure 6. The particulates were not completely removed as the processing time was rather short. The cavity temperature did not exceed 48°C.

CONCLUSIONS AND FUTURE DEVELOPMENT

The in-situ ECR plasma can be very flexible compared to the other plasma techniques. The sample experienced short processing time showed the processing will likely be effective for sulfur contaminant. How oxygen will alter the surface oxide composition remains to be explored. Cavities will experience more varieties of contaminants. The final cavity performance will hinge on the successful removal of all contaminants while not compromising surface quality. Future studies will be focused on finding an optimized procedure and gas mixtures to effectively remove as many contaminants as possible and their effects on surface composition. RF test using single cell cavities will be employed to finally qualify the best procedure.

ACKNOWLEDGEMENT

The experiment got help from R. Nehring, R. Fliller, J. Santucci, G. Lauten, and R. Lewis from Fermilab. We would like to thank our Jefferson Lab colleagues such as P. Kneisel, B. Manus, G. Slack, L. Phillips, G. Biallas, R. Rimmer, C. Reece, H. Wang and G. Ciovati for their help and discussion. We also thank H. Padamsee for the discussion and for his suggestions about the sample tests.

REFERENCES

[1] S.M. Rossnagel, J.J. Cuomo, and W.D. Westwood, eds. Handbook of Plasma Processing Technology: Fundamentals, Etching, Deposition, and Surface Interactions (Materials Science and Process Technology) 1990, Noyes Publications. 523.
[2] R.J. Shul and S.J. Pearton, eds. Handbook of Advanced Plasma Processing Techniques. 1 ed. 2000, Springer. 653.
[3] Dylla, H.F., “Glow discharge techniques for conditioning high-vacuum systems”. Journal of Vacuum Science and Technology, 1987. 6(3): p. 12.
[4] William E. Cohen, R.M.G., Reginald L. Jaynes, Christopher W. Peters, and Y.Y.L. Mike R. Lopez, Scott A. Anderson, and Mary L. Brake, Thomas A. Spencer, Radio-frequency plasma cleaning for mitigation of high-power microwave-pulse shortening in a coaxial gyrotron. APPLIED PHYSICS LETTERS, 2000. 77(23): p. 3.
[5] M. Chen and R. H. Wang, J.Vac.Sci. Technol. A, Vol. 1, No. 2, Apr/June 1983
[6] Jay N. Sasserath and John Vivalda, J.Vac.Sci. Technol. A, Vol. 8, No. 6, Nov/Dec 1990
[7] L. Phillips, private communication
[8] N. Patron, R.B., L. Phillips, M. Rea, C. Roncolato, D. Tonini, and V. Palmieri. Plasma cleaning of cavities. in Thin Films and new ideas for pushing the limits of RF superconductivity. 2006. Padua, Italy.