LARGE-VOLUME RESONANT MICROWAVE DISCHARGE FOR PLASMA CLEANING OF A CEBAF 5-CELL SRF CAVITY

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Abstract

We report the preliminary results on plasma generation in a 5-cell CEBAF superconducting radio-frequency (SRF) cavity for the application of cavity interior surface cleaning. CEBAF currently has ~300 of these five cell cavities installed in the Jefferson Lab accelerator which are mostly limited by cavity surface contamination. The development of an in-situ cavity surface cleaning method utilizing a resonant microwave discharge could lead to significant CEBAF accelerator performance improvement. This microwave discharge is currently being used for set of plasma cleaning procedures targeted to the removal of various organic, metal and metal oxide impurities. These contaminants are responsible for the increase of surface resistance and the reduction of RF performance in installed cavities. CEBAF cavity has a cylindrical symmetry, but its elliptical shape and transversal power coupling makes it an unusual plasma application, which requires special consideration of microwave breakdown. Our preliminary study includes microwave breakdown and optical spectroscopy, which was used to define the operating pressure range and the rate of removal of organic impurities.

INTRODUCTION

The benefits of plasma cleaning for SRF cavities are wide ranging. It has been shown [1] that plasma cleaning reduces field emission, cleans RF surfaces leading to stable vacuum in the cavity and can reduce the number of accelerator interlock trips. While it has been proven to be an inexpensive way to increase gradients limited by surface contaminates, the successful procedure has the potential to reduce the effects of Q-disease and oxides from the cavity surface. Moreover, the ability of plasma to follow the shape of solid vessel will make it most suitable for cleaning complex, asymmetric surfaces in geometrically complicated SRF cavities such as quarter wave and spoke designs.

When prepared to generate a uniform microwave discharge in a multi-cell SRF cavity one has to recognize several issues. The problems can be grouped in two categories; first to develop a successful procedure where the peripheral components are not damaged. This category requires a mock experimental setup for the plasma generation to develop procedures where the risk of damaging expensive components is minimized. This process we call *ex situ*, where full access to the cavity and peripheral components is available. This process entails qualifying a cavity in vertical test for a baseline RF performance, treating the cavity by plasma cleaning procedure, and again, tested for RF performance to bracket changes in performance. While less complex from plasma generation point of view, *ex situ* processing can be well understood and instrumentation and procedures can be easily developed.

The second category is *in situ* processing of cavities mounted within a cryostat. Here the processing only has access to the instrumentation and signals available in that cryostat design, complicating the understanding of the discharge dynamics and the kinetics of plasma cleaning.

The common problem with both *ex situ* and *in situ* processing of SRF cavities is developing the discharge in the cell region and not on an input coupler or ceramic window area. Surface discharge at the window or RF coupler will reduce or diminish the RF performance. This complication extends further if the processing is performed at cold temperatures the uncertainty of the gas discharge pressure and localized density arising from cryogenic pumping on cold surfaces. Due to this problem our first effort focuses on discharge plasma at room temperature. At room temperature typically the RF coupling to the cavity is very weak due to the cavity Q-value at these temperatures and therefore requires significant amplifier power to achieve the discharge.

In this paper, we present our results of the large-volume plasma generation in the CEBAF 5-cell cavity at resonant power coupling conditions, similar to the actual set-up in the cryomodule. In the first section we describe the set-up and present the results on microwave breakdown. In the second section we present preliminary data on volatile impurity spectra, outline the optimal pressure range, and estimate the time scale of plasma cleaning with Ar/O_2 mixture. We conclude with confirmation of the versatility and effectiveness of the technique, and with suggestions for future work.

MICROWAVE BREAKDOWN

In our preliminary experiment, we have coupled microwave power to a five-cell cavity at resonant frequency at room temperature, where low conductivity of Niobium yields cavity Q factor of the order of 10^4, that is, six orders of magnitude below the value at cryogenic conditions.

Experimental observation of microwave breakdown in resonant cavities has been prescribed by Raizer [2]. The electric field at the axis is increased by bringing up the power fed to the cavity until the transmitted power falls abruptly. This is the sign of breakdown that can be measured without visual or any other optical detection. The corresponding field at the axis is considered then as the microwave breakdown field. Immediately after breakdown, plasma expands to the wall, forms the sheath, and starts interacting with the surface.

Following the steady state approximation, and neglecting the electron loss due to the electron attachment to oxygen atoms we now proceed from the steady-state breakdown criterion where ionization is compensated by diffusion losses, $\nu_i = \nu_{diff} = D/\Lambda^2$, where D is the electron diffusion coefficient and Λ is the effective diffusion length. This stationary criterion may lead to the doubling of electron density in about 1 μs, which is a good approximation even in the case of microwave breakdown. We will treat here the low pressure case, since it provides more energetic radicals that are needed for surface processing. We recall that most electrons do not retain energy received by the field above lowest excited energy level $\Delta E^*_{Ar} \sim 11\ eV$ in Argon or Argon dominated mixtures. In the occasion that an electron gets higher energy, it immediately looses it in an inelastic collision.

The ionization is carried on by a cascade process, which results in the quadratic dependence of the ionization rate on the electric field amplitude:

$$\nu_i = \frac{e^2 E^2 \nu_m}{m\omega^2 \Delta E^*_{Ar}} = \frac{D}{\Lambda^2} \qquad (1)$$

for the free diffusion,

$$D = \left\langle v^2 / 3\nu_m \right\rangle \approx \frac{\ell \bar{v}}{3} \quad \Rightarrow \quad D \sim \frac{1}{p}$$

and, in the flat cylinder approximation

$$\frac{1}{\Lambda} = \sqrt{\left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2}$$

where $\ell, \bar{v}$ are the electron mean free path and average velocity, respectively, p is the gas pressure, R and L are the effective radius and the length, and we have applied the steady-state breakdown criterion. Consequently, breakdown root-mean-square field can be expressed as follows [3]:

$$E_t \Lambda = const \times (p\lambda)^{-1} \qquad (2)$$

where $E_t\Lambda$ is the product of the breakdown rms electric field and the effective diffusion length. The coefficient of proportionality depends on gas temperature, collision cross section, and the excitation energy of the lowest state. Magnetic field strength slightly below critical ($B \approx 0.1\ T$) should affect electron diffusion and, in principle, the diffusion length has to be recalculated with the effect of magnetic field being measured by the cyclotron frequency

$$\nu_b = \frac{eB}{2\pi m}$$

Assuming uniform radial distribution of the transversal magnetic field, the diffusion length for elliptical cavity is further expanded into [3,4]:

$$\frac{1}{\Lambda^2_{b,ellip}} = \frac{1}{L} \int_{z=0}^{z=L} \left\{ \frac{\nu_i^2}{\nu_i^2 + \nu_b^2} \left[\left(\frac{\pi}{L}\right)^2 + \frac{1}{2}\left(\frac{2.405}{R(z)}\right)^2 \right] + \frac{1}{2}\left(\frac{2.405}{R(z)}\right)^2 \right\} dz \qquad (3)$$

where $R(z)$ outlines the elliptical profile of the cavity.

Low pressure trend of the breakdown curve is as expected. $E_t\Lambda$ has a hyperbolic dependence on the product of gas pressure and microwave wavelength, $p\lambda$, in accordance with the discussion on the resonant microwave breakdown by Brown [4]. For the resonant cavity, the effective diffusion length Λ and the wavelength λ are a constant, leading to the hyperbolic dependence of electric field on the pressure, as seen in Fig. 1. Breakdown formula (2) is derived after neglecting electron attachment losses, which is justified by the experiment, where the observed breakdown power is identical for pure Argon and for Argon/Oxygen (9:1) mixture. Higher oxygen concentration may require inclusion of the attachment losses in the calculation.

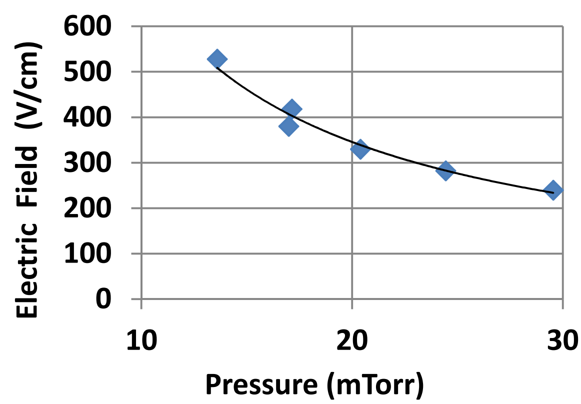

Figure 1: Dependence of breakdown field on pressure for the 3π/5 mode. Solid line is the hyperbolic fit (power -1).

EXPERIMENTAL SET-UP AND SPECTRAL ANALYSIS

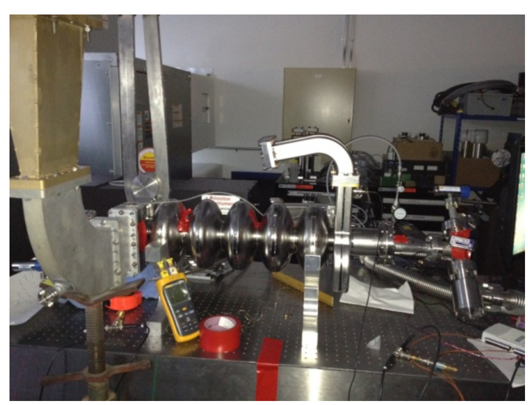

Figure 2: Microwave plasma apparatus.

Experimental set-up is shown in Fig. 2. The photo of the plasma inside the 5-cell cavity, as seen through the sapphire window at the cell axis, is given in Fig.3.

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Figure 3: End-on view of the microwave discharge plasma glow.

Spectroscopic study was made using a sapphire window positioned at the end of the cavity. Observational column was, therefore, about 1 m long, and 5×25 μm wide. The recorded spectra from this experimental setup had both emission and absorption features, the later being wider and less distinct. A typical spectral frame is given in Fig.4.

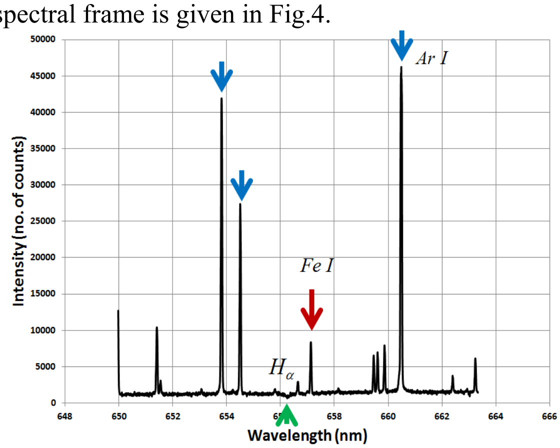

Figure 4: Spectral frame around 656 nm showing Argon spectral lines (blue arrow), an Iron impurity line, and Hydrogen H_α line in absorption (green arrow).

Optical spectrum analysis can be used for measuring impurity removal rates from the cavity walls. As a first example let us consider the rate of removal of organic compounds from the cavity walls. Organic compounds sticking on the surface are being removed in reactions of oxygen ions and metastables. In this example, one product of these reactions is OH, which is identified in the emission spectrum. Based on the relative measurements of OH band intensity, we can estimate the rate of removal of organics from the walls, using OH as a signature for the removal. Our preliminary data gives the integrated intensity ratio (*IIR)* as:

$$IIR(t) = 1.26e^{-t/\tau}, \qquad \tau = 16.7 \text{ min}$$

Working pressure range for plasma cleaning by Ar/O_2 ("ashing") can be obtained by plotting relative intensity of a set of Ar spectral lines within a single spectral frame normalized to average intensity of baseline noise. This is the measure of excitation of plasma produced radicals to be used for cleaning the surface from organics. A preliminary result based on the normalized line intensity (NLI) fit gives

$$NLI(p) = 7.55\, e^{-p/p_r}$$

$$p_r \cong 150\, mTorr$$

The obtained value of pressure constant p_r is consistent with the recommended range for cleaning by ashing p < 100 mTorr.

CONCLUSION

Large-volume plasma discharge was generated in a CEBAF 5-cell cavity with Ar and Ar/O_2 mixtures. This experimental setup used a similar coupling configuration as in the standard CEBAF cryomodule design. The cavity voltage was driven by a solid state 500 Watt amplifier and a tuneable RF frequency source. Microwave breakdown curve for Ar and its mixture with oxygen shows qualitative agreement with the simplified breakdown theory that assumes electron diffusion as a main loss. Although present configuration is not optimized for optimum power coupling, preliminary spectroscopy data show that the plasma cleaning process has been achieved with respect to organic and some residual metallic impurities, however additional effort is needed to make the process reliable. The ongoing development of this application will be focused on the power coupling issues, measurements of cleaning rates and development of a repeatable *in-situ* plasma cleaning procedure.

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