TOMOGRAPHIC ANALYSIS OF SRF CAVITIES AS ASYMMETRIC PLASMA REACTORS

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Abstract

The tomographic reconstruction of local plasma parameters for nonequilibrium plasma sources provides deep insight into the fundamental processes and phenomena during plasma processing of superconducting radio frequency (SRF) cavity surfaces. A plasma processed SRF cavity represents a plasma reactor with limited or distorted symmetry, and possible presence of high gradients. Application of the tomographic method for SRF plasma analysis consists of several steps. First, we define the method based on the inversion of the Abel integral equation for a hollow spherical reactor. The second step is the application of the method for the actual elliptical cavity shape. The third step consists of the study of the effects of various shapes of the driven electrode. The final step consists of testing the observed line-integrated optical emission data.

INTRODUCTION

Niobium (Nb) with its superconducting properties is the most favorable material for building SRF cavities. In order to achieve theoretically predicted values of accelerating fields, the processed surface of SRF cavities should have small surface roughness with no additional impurities. Acid-based wet technologies, such as buffered chemical polishing (BCP), or electrochemical polishing (EP) are standard methods in achieving these goals. These techniques are costly and, most of all, environmentally unfriendly. Our aim is to introduce an alternative procedure which would decrease the cost and the environmental pollution and would exceed the performances of liquid etching. A plasma based dry etching offers a promising approach for the treatment of Nb surfaces. A similar approach has already been employed in preparation of superconducting devices and is a vital technology in semiconductor material processing. Experiments done on flat samples [1] proved that etching rates and surface roughness are comparable to wet etching processes.

The geometry of SRF cavities requires that the RF discharge to be asymmetric. The asymmetry of the discharge causes a difference in the voltage drop over the plasma sheath attached to the driven electrode and the plasma sheath attached to the cavity surface. To achieve the effective asymmetric discharge, i.e. uniform etching and good enough RF cavity performance, the voltage of the undriven, grounded electrode should be at least equal or higher to the plasma floating potential at every point of the surface. A specially designed single cell cavity is being used to investigate these asymmetric discharges and their properties. We should confirm the uniform distribution of the plasma sheath over the inner surface by using the cavity with twenty symmetrically spaced holes covering every segment of the surface (see Fig 1). Optical intensities of the discharge are measured and combined with the direct etched surface diagnostics to determine the plasma properties.

The tomographic analysis of SRF cavities is a developing technique employed in the further study of the plasma parameters. First, we are describing the radial profiles of the optical intensities based on the inversion of the Abel integral equation in case of cylindrical symmetry. Then, we are testing the method by employing different cavity shapes. The final goal is to introduce the tomography methods in two and three dimensions.

EXPERIMENTAL APPROACH

To perform the plasma processing on single cell cavity, a bell jar system has been developed. The single cell cavity has 20 sample holders symmetrically placed on the ellipsoid of the cavity (Fig. 1). These sample holders can be used as diagnostic ports to measure plasma properties as well as to hold the niobium samples to be etched. The whole bell jar is kept under vacuum with a rotary and turbo pump combination. The discharge is created with a AC discharge power supply and a specially designed electrode.

Figure 1: Multiple optical fiber set-up for single cell cavity.

The plasma is produced in argon and the gas flow is measured with flow meter.

Since a thin Nb rod electrode creates an asymmetric discharge, we designed an electrode which follows the geometry of the cavity to partially overcome this feature. To determine the plasma properties, a multiple point optical probe has been developed. The 1 mm diameter optical fiber, recessed inside a ceramic tube, is placed on multiple sample holders of the cavity with feed throughs. We take simultaneous spectral measurements of the plasma from these fibers with the help of a spectrometer and a ccd camera.

PLASMA TOMOGRAPHY

Abel Inversion

Spectral line intensities obtained by different spectroscopic methods (emission spectroscopy, absorption spectroscopy, etc.) in side-on measurements depend on a radial emission coefficient, $\varepsilon(r)$. The Abel inversion provides the information about the radial population distribution.

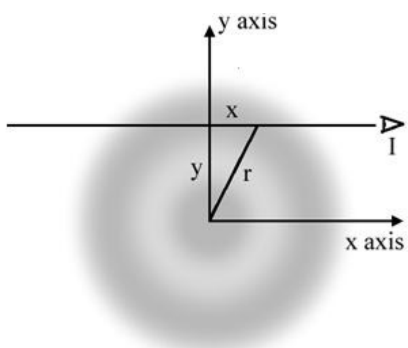


Figure 2: Schematic of the cylindrical symmetry of a discharge.

Assuming the cylindrical symmetry (see Fig 2), measured line intensities depend on radial emission coefficient [4],

$$I(y) \;=\; 2\int_y^R \frac{\varepsilon(r)rdr}{\sqrt{r^2-y^2}}. \qquad (1)$$

Then, the radial emission coefficient is,

$$\varepsilon(r) \;=\; -\frac{1}{\pi}\int_r^R \frac{I'(y)}{\sqrt{y^2-r^2}}dy, \qquad (2)$$

where $I'(y)$ is the first derivative of $I(y)$ with respect to y and R is the radius of a tube.

In order to test the numerical model we employed a plasma discharge maintained in the cylindrical, quartz cavity at atmospheric pressures. We performed a detailed characterization of the afterglow region of the supersonic flowing microwave discharge obtained in the pure Ar and Ar with 1% hydrogen mixture. Optical emission spectroscopy was used as a diagnostic tool for observing the spectra of the excited and ionic Ar states [2]. The populations of the Ar I excited states at 2.4 Torr were measured at several distances from the microwave cavity. Figure 3 shows the population of the Ar I 4p[3/2] $\rightarrow$ 4s[3/2]^o transition at 714 nm. We also measured the intensities of the Ar I 6s[3/2]^o $\rightarrow$ 4p[5/2] spectral line at 710 nm and Ar I 4p[3/2] $\rightarrow$ 4s[3/2]^o spectral line at 706 nm [3].

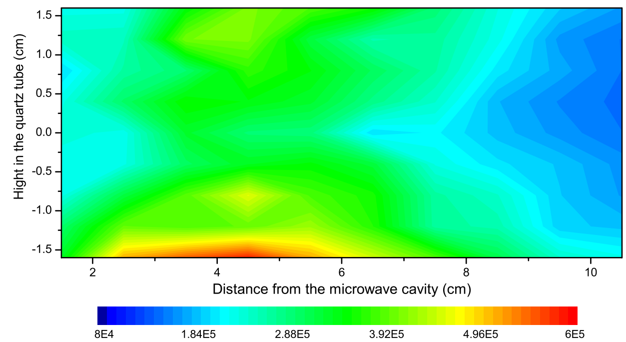


Figure 3: Intensity of the Ar I 4p[3/2] $\rightarrow$ 4s[3/2]^o transition at 714 nm, 2.4 Torr.

We obtained the radial profiles of the measured spectral intensities as a function of the distance from the center of the microwave cavity by applying Eq. (2). The results are presented in Fig. 4. It is evident from this figure that the argon ions are mostly located close to the inner surface of the quartz tube implying that the discharge is partially sustained with the surface wave which is in a good agreement with our theoretical predictions.

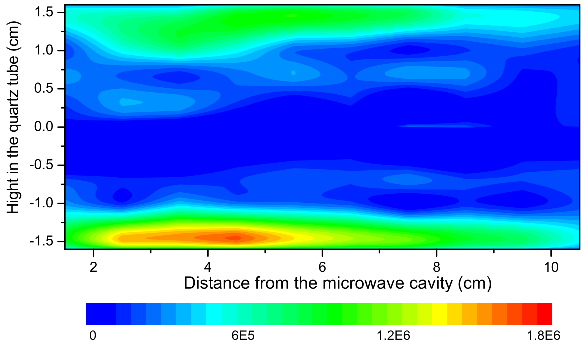
Asymmetric discharge

In the case the plasma is not cylindrically symmetric, it is possible to obtain the volume emission coefficient by measuring the spectral intensities in two mutually perpendicular directions. Then the volume emission coefficient is assumed to have radial and angular dependence [4],

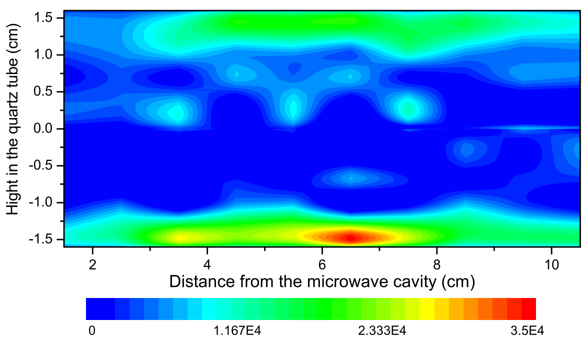
$$\varepsilon(r,\theta) \;=\; H(r) + K(r)cos\theta + L(r)sin\theta, \qquad (3)$$

where θ = 0 is taken along the x-axes. If $I(x)$ and $I(y)$ are measured intensities in x and y directions, then measured spectral intensities are related as

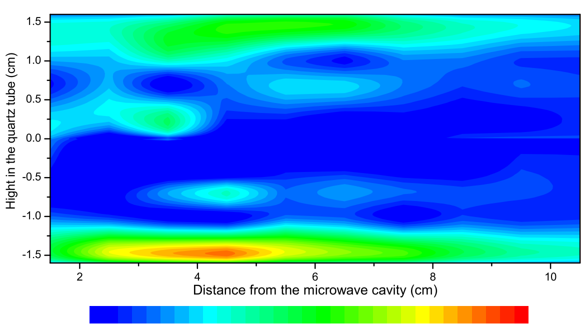
$$\begin{aligned}
\tfrac{1}{2}(I(x)+I(-x)) \;&=\; 2\textstyle\int_x^R \frac{H(r)rdr}{\sqrt{r^2-x^2}}\\
\tfrac{1}{2x}(I(x)-I(-x)) \;&=\; 2\textstyle\int_x^R \frac{K(r)}{r}\frac{rdr}{\sqrt{r^2-x^2}}\\
\tfrac{1}{2}(I(y)+I(-y)) \;&=\; 2\textstyle\int_y^R \frac{H(r)rdr}{\sqrt{r^2-y^2}}\\
\tfrac{1}{2y}(I(y)-I(-y)) \;&=\; 2\textstyle\int_y^R \frac{L(r)}{r}\frac{rdr}{\sqrt{r^2-y^2}}.
\end{aligned} \qquad (4)$$



(a) Population of Ar I at 706 nm.



(b) Population of Ar I at 710 nm.



(c) Population of Ar I at 714 nm.

Figure 4: Population of different Ar I lines at 2.4 Torr in supersonic flowing MW discharge.

It can be seen that the above equations are similar to Eq. (1) for cylindrical symmetry. This means that we can evaluate $H(r)$, $K(r)$ and $L(r)$ by applying the Abel inverted integral, Eq. (2).

Our main goal is to apply the described numerical method on the asymmetric discharge inside the SRF cavity. Thus, we would be able to study the distribution of the plasma sheath over the inner surface of the cavity.

CONCLUSION

We have studied the radial profiles of the optical intensities using one dimensional inverse Abel integral. The model has been tested on supersonic flowing MW discharge maintained in the cylindrical quartz tube. The promising results allow us to introduce the two dimensional tomography which will be applied on the asymmetric discharge in an SRF cavity.

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