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SURFACE RESISTANCE RF MEASUREMENTS OF MATERIALS USED FOR ACCELERATOR VACUUM CHAMBERS

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Abstract

The RF surface resistance of accelerator vacuum chamber walls can have a significant impact on the beam quality. There is a need to know how the use of a new material, surface coating or surface treatment can affect the RF surface resistance. ASTeC and Lancaster University have designed and built two test cavities where one face can be replaced with a sample in the form of a flat plate. The measurements are performed with a network analyser at the resonant frequency of approximately 7.8 GHz.

INTRODUCTION

If one considers the formulation of the unloaded quality factor Q_0 of an RF cavity [1] one can write

$$Q_0 = \frac{2\pi f_0 \mu_0 \iiint_V |\boldsymbol{H}|^2.dV}{\iint_S R_S |\boldsymbol{H}|^2.dS} \quad (1)$$

where H is the magnetic field, R_S is the surface resistance of the cavity walls and f_0 is the resonant angular frequency of the cavity. To accommodate the possibility of a cavity being comprised of two parts (a cavity and a sample) which could be made of different metals or otherwise have different R_S values, one can most conveniently rewrite this as

$$Q_0 = \frac{G}{R_S^{sample} p_S + R_S^{cavity} p_C} \quad (2)$$

where G is the geometry constant of the cavity [1], defined as

$$G = \frac{2\pi f_0 \mu_0 \iiint_V |\boldsymbol{H}|^2.dV}{\iint_S |\boldsymbol{H}|^2.dS} \quad (3)$$

R_S^{sample} and R_S^{cavity} are the surface resistance of the sample and the cavity respectively, and p_S and p_c the sample and cavity ratios – the proportion of the total field dissipated over their respective surfaces, i.e.

$$p_S = \frac{\iint_{sample} |\boldsymbol{H}|^2.dS}{\iint_S |\boldsymbol{H}|^2.dS} \quad (4)$$

$$p_C = \frac{\iint_{cavity} |\boldsymbol{H}|^2.dS}{\iint_S |\boldsymbol{H}|^2.dS} = 1 - p_S \quad (5)$$

For any similarly-shaped cavity G and p_S are in principle constant, irrespective of the materials used.

This implies that, knowing R_S^{cavity}, G and p_S for a given cavity we can calculate R_S for any sample by placing it on top of the cavity and finding the unloaded Q-factor of the resulting RF resonance.

$$R_S^{sample} = \frac{G/Q_0 - R_S^{cavity}(1-p_S)}{p_S} \quad (6)$$

METHOD

Calculation of Q_0

Two double-choked pillbox-type cavities were used to take our measurements, one of which can be seen in Fig. 1. The choked cavity allows the testing of flat samples without the need for flanges and RF seals. Both cavities were manufactured to identical dimensions by Niowave Inc. [2], one being made from aluminium and one from niobium.

Figure 1: A two-choked 8 GHz Al test cavity.

In each case the samples, in the form of flat plates or discs of sufficient width to completely cover the outer choke, were placed on top of the cavity with spacers providing a gap of ~2 mm between the cavity and the sample. An axially-mounted coaxial antenna was attached to a calibrated network analyser to induce RF resonance, and the coefficient of signal reflection (S_{11}) measured against frequency. Initial setup required that the spacing between the sample and the cavity was adjusted to

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maximise signal loss near the resonant frequency of the first mode (approximately 7.8 GHz). The probe depth was adjusted to induce near-critical coupling, as judged from a Smith Chart of S_{11}. [3]

Q_0, was calculated using the formula

$$Q_0 = \frac{f_0}{f_2+f_3-f_1-f_4} \quad (7)$$

where f_1 and f_2 are the frequencies at which the imaginary components of S_{11} are minimal and maximal respectively with the system in the detuned open position. f_3 and f_4 are the frequencies at which the imaginary component of S_{11} are ∓ 1 respectively in the detuned open position. [3]

Calculation of Surface Resistance from First Principles

The surface resistance R_S of a metal under AC stimulation depends on four factors; its bulk electrical resistivity ρ and magnetic permeability μ, the AC frequency f and its surface roughness. In the GHz regime all four are important contributors to R_S. For a perfectly smooth metal surface (with zero roughness)

$$R_S = \sqrt{\pi \mu_0 f \rho} \quad (8)$$

to account for the effect of the finite skin depth in the metals under AC excitation [1].

Hammerstad and Bekkadal (1975) produced an empirical formula describing the effect of the RMS roughness, R_Q, on R_S. Based on their observations [4] an additional factor applies as follows:

$$R_S = \left(1 + \frac{2}{\pi}\tan^{-1}\left(1.4 \times {R_Q}^2 \times \frac{\pi \mu f}{\rho}\right)\right) \quad (9)$$

The sample surface roughness was calculated using measurement data from an interferometric microscope by scanning the surfaces of five metal samples: metal discs made of Cu, Al, Nb and 304 Stainless Steel and a ~5 µm-thick Cu film deposited via pulsed DC magnetron sputtering onto a Silicon (100) wafer.

A theoretical value of R_S was then calculated for each sample using the modified formula (9) above.

Due to its physical dimensions the available interferometric microscope could not be used to obtain a roughness profile for the surface of the cavities themselves. As a consequence, only an upper limit was set on their R_Q, and hence R_S, based on the manufacturer's specifications.

Comparison of Measured and Theoretical Results

The first step in an attempt to validate this method was to plot the calculated and measured values of R_S^{sample} for all samples against one another. The data from both cavities was observed to be in good agreement (coefficient of determination > 0.97) to a linear relationship. A manual iterative method was used to find the values of R_S^{cavity}, G and p_S for which the relationship most closely approximated $y = x$. As would be expected such values of G and p_S were the same for both cavities, at ~224 and ~0.37 respectively.

These figures were then used as the starting point for a more precise fitting technique, using MathCAD [5]. Here, for each value of p_S and R_S^{cavity}, R_S^{sample} was swept across a small range of values and the point at which both cavities returned the same value of G was logged. It was observed that the returned value of G was 225 for all sample-cavity combinations, to within the standard deviation of the measurements, when $p_S = 0.375$.

This matched very closely with values for G and p_S calculated from first principles using a CST [6] Microwave Studio simulation (shown in Fig. 2): $G = 224$ and $p_S = 0.375$.

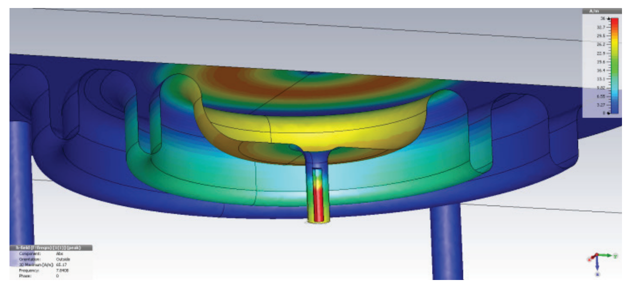

Figure 2: Simulated distribution of the H-field on the sample (top) and cavity and chokes (bottom).

RESULTS AND DISCUSSION

Table 1 shows the calculated values of R_S at RF frequency f = 7.8 GHz.

Table 1: Calculated Values of R_S at 7.8 GHz

Sample	ρ(Ωm)	R_Q (m)	R_S (mΩ) calc
Cu plate	1.72×10^{-8} [7]	4.09×10^{-7}	28.6
Al	2.73×10^{-8} [7]	4.05×10^{-7}	34.0
304 SS	7.20×10^{-7} [8]	1.44×10^{-6}	160
Nb	1.52×10^{-7} [7]	(1×10^{-6})	80.7
Cu film	1.72×10^{-8} [7]	9.08×10^{-6}	22.7

Note that $\mu \approx \mu_0$ [7, 8] for all the materials we used. Table 2 shows the mean value of Q_0 for each cavity-sample combination from sets of five consecutive calculations - removing, rotating and replacing the sample between each one.

The uncertainty comes from combining (as the root of the sum of the squares) the relative standard deviation within these sets of readings and the estimated relative error in the measurements of f_0, f_1, f_2, f_3 and f_4.

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Table 2: Mean Q_0 of 7.8 GHz Cavity Resonance

Sample	Q_0 (Al cavity)	Q_0 (Nb cavity)
Cu plate	5398 (+ 0.77%)	3368 (+ 1.54%)
Al	4787 (+ 2.28%)	2981 (+ 4.16%)
304 SS	2382 (+ 1.98%)	1941 (+ 0.64%)
Nb	3957 (+ 1.27%)	2703 (+ 1.26%)
Cu film	5333 (+ 2.07%)	3324 (+ 1.98%)

Table 3 shows the resultant values of R_S^{sample} for each cavity-sample combination, as well as those calculated from first principles.

The calculations used some values which it was not possible to obtain from literature or determine from direct measurement:

- For both cavities a value of $G = 255$ and $p_S = 0.375$ were used, from the MathCAD best-fit solution (supported by the CST calculations)
- R_Q for the cavities was assumed to be that which gave the best $y = x$ fit to the data.
- R_Q for the Nb plate comes from the manufacturer's specifications.

Table 3: Comparison of the Values of R_S calculated from First Principles and from the Q_0 Readings for 7.8 GHz Al and Nb Cavities

Sample	R_S, calculated (Ω)	R_S^{sample} from Q_0 , Al (Ω)	R_S^{sample} from Q_0 , Nb (Ω)
Cu film	2.27 x 10^{-2}	2.84 x 10^{-2}	2.34 x 10^{-2}
Cu plate	2.86 x 10^{-2}	2.70 x 10^{-2}	2.09 x 10^{-2}
Al	3.36 x 10^{-2}	3.85x10^{-2}	4.43 x 10^{-2}
304 SS	1.60 x 10^{-1}	1.68x10^{-1}	1.52 x 10^{-1}
Nb	8.06 x 10^{-2}	6.75x10^{-2}	6.49 x 10^{-2}

Table 4: Comparison of the Values of ρ calculated from the Literature and from the Q_0 Readings for 7.8 GHz Excitation of the Al and Nb Cavities

Sample	ρ (Ωm)	ρ from Q_0 , Al (Ωm)	ρ from Q_0 , Nb (Ωm)
Cu film	1.72×10^{-8} [7]	2.61×10^{-8}	1.77×10^{-8}
Cu plate	1.72×10^{-8} [7]	2.36×10^{-8}	1.42×10^{-8}
Al	2.73×10^{-8} [7]	4.79×10^{-8}	6.35×10^{-8}
304 SS	7.20×10^{-7} [8]	9.13×10^{-7}	7.49×10^{-7}
Nb	1.52×10^{-7} [7]	1.47×10^{-7}	1.36×10^{-7}

The results suggest that this is have here a useful and robust method for determining R_S^{sample}. The internal consistency of our results suggests that its effect on Q_0 is as is expected, and that G, p_S and p_C can be accurately calculated for a cavity of this sort using CST Microwave Studio. The empirical formula for the surface resistance of a rough surface means that we can either calculate R_S^{cavity} from first principles or, if measuring the cavity R_Q is not practical, find a good estimate for it via the best fit to the data from several 'calibration' samples. Therefore, once we measure Q_0 on that cavity for each subsequent unknown sample we have all the components we need to calculate R_S^{sample}.

Possible sources of systematic error include:

- The assumption that the metal remains in the normal skin-depth regime.
- The roughness-modified formula for R_S is only an approximation.
- The fact that the samples we used might have a different bulk resistivity to that given by the literature.
- Surface oxidation, dirt, and/or fractures beneath the surface of the sample could all also have had an effect on R_S which is not currently quantifiable.

Coupling losses cannot be accounted for.

The cavity was originally designed to measure R_S^{sample} at cryogenic temperatures [9]. If the bandwidth permits, we will try to duplicate the measurements using the method described above, but we plan to use calorimetric methods which will afford a far more reliable method of measuring the much-higher Q-factors. Additional considerations, and details of the apparatus, are covered in another paper [9].

CONCLUSION

The method of measuring RF surface resistance using two-choke test cavities at room temperature was analytically developed and implemented in two cavities made of Al and Nb. Measured values of R_S for Cu, Al, Nb and 304 stainless steel are in a good agreement with theoretically calculated values.

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