MEASUREMENTS OF FREQUENCY, TEMPERATURE, RF FIELD DEPENDENT SURFACE RESISTANCE USING SRF HALF WAVE CAVITY*

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Abstract

A theory of surface resistance of superconductor was rigorously formulated by Bardeen, Cooper, Schrieffer more than 50 years ago. Since then the accelerator community has been used the theory as a guideline to improve the surface resistance of the superconducting cavity. It has been observed that the surface resistance is dependent on frequency, temperature and rf field strength, and surface preparation. To verify these dependences, a well-controlled study is required. Although many different types of cavities have been tested, the typical superconducting cavities are built for specific frequencies of their application. They do not provide data other than at its own frequency. A superconducting half wave cavity [1] is a cavity that enables us to collect the surface resistance data across frequencies of interest for particle accelerators and evaluate preparation techniques. This paper will present the design of the half wave cavity, its electromagnetic mode characteristics and experimental results in order to better understand the contributions of the various physical processes to the surface resistance of superconductors.

INTRODUCTION

So far, the origin of residual resistance is believed to be a result of extrinsic mechanisms such as trapped vortices, metallic suboxide layers at the surface, non-superconducting precipitates (hydrides, etc) [2]. The full theory should include residual resistance. Extracting frequency, temperature, rf field dependence will provide significant insight to a better understanding.

Because of the statistical nature of multiple materials defect, technological contributions to surface resistance and the lack of reproducibility, it is difficult to extract accurate frequency dependence of the surface resistance when different cavities of different frequencies are tested. Coaxial half wave resonator provides the frequencies reasonably separated and the same location where the high surface magnetic field is distributed.

CAVITY DESIGN

For our research purpose a cavity should meet a certain requirements as listed below.

- Cavity should provide a wide range of frequency, preferably frequencies used in accelerators.
- Different modes should be widely separate so the measurement can be easily made.
- Cavity should be able to reach high rf surface field.
- Mechanically compatible with various cavity treatment.

We chose a half wave coaxial cavity. The TEM modes of this cavity can provide the frequencies of interest: 325, 650, 975, 1300 MHz. These TEM modes are sufficiently separated by other TM and TE modes by strategically dimensioning the cavity inner radius (20 mm) and outer diameter (101 mm). The rf properties of each mode are shown in Table 1. Surface field distribution of each mode is shown in Figure 1.

Table 1: RF Properties of Half Wave Coaxial Cavity

Mode	Frequency [MHz]	Geometric factor	R/Q [Ohm]
TEM1	325.4	59	124
TEM2	650.8	119	62
TEM3	976.1	179	41
TEM4	1301.3	239	31

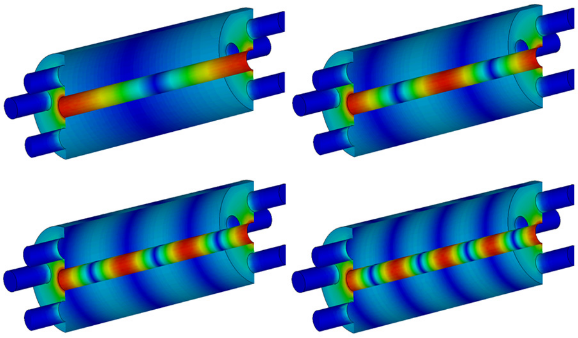

Figure 1: Surface magnetic field distribution from top left to right TEM1, TEM2, and from bottom left to right TEM3 and TEM4.

EXPERIMENTAL METHODS

As a baseline, we prepared the cavity using following typical cavity processing.

- Bulk BCP 150 µm removal.
- Heat treatment at 600 °C for 10 hours.
- Light BCP 10 µm removal.
- High pressure rinse.
- Evacuation and leak check.
- Bake at 120 °C for 24 hours.

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Before cool down, temperature gages (Cernox) were installed throughout the cavity surface to measure the cool down rate. Figure 2 is showing the cavity cool down rate around the critical temperature. The slowest cool down location had about 0.5 K/min.

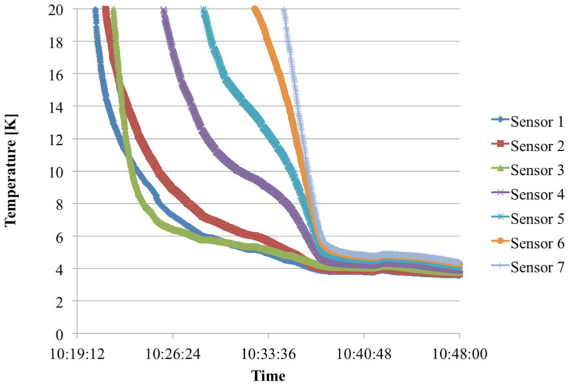

Figure 2: Cool down rate.

When the cavity reached 4K, we started to make decay measurement at low field and calculate quality factor of the cavity as the cavity cools down. Figure 3 is showing the quality factor plot during the decay measurement of 325 MHz as cavity cools down.

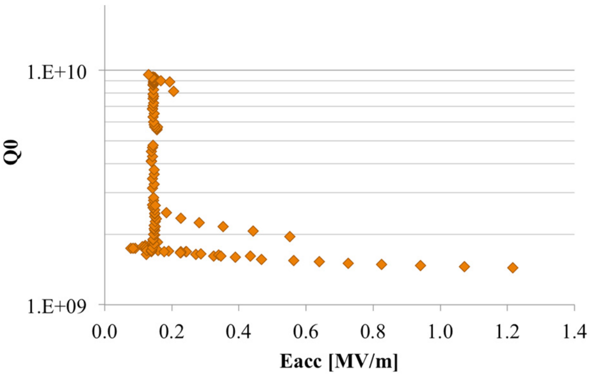

Figure 3: Quality factor measurement of 325 MHz while temperature was cooling down from 4K to 2K.

Surface resistance is calculated from the relationship of

$$Q_0 = \frac{\omega_r U}{P} = \frac{\omega_r \int \mu_0 |\boldsymbol{H}|^2 \, dv}{\frac{1}{2} R_s \int |\boldsymbol{H}|^2 \, da} = \frac{G}{R_s} ,$$

where Q_0, ω_r, U, P, μ_0, $\boldsymbol{H}$, R_s and G are intrinsic quality factor, resonant angular frequency, stored energy, loss, permeability in vacuum, magnetic field, surface resistance and geometric factor respectively. Figure 4 is showing the surface resistance calculated from quality factors from Figure 3.

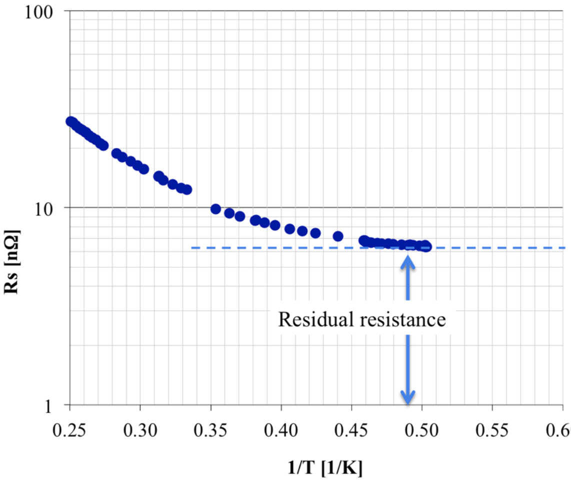

Figure 4: Surface resistance as a function of 1/T.

PRELIMINARY TEST RESULTS

Surface resistance of all 4 frequencies are summarized in Figure 5.

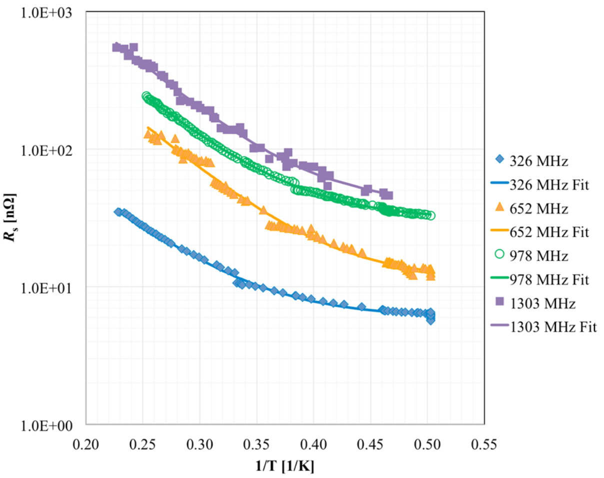

Figure 5: Surface resistance as a function of temperature for 325, 650, 975 and 1300 MHz.

The surface resistance curves are then fitted to extract BCS resistance and residual resistance using the formula from BCS theory [2].

$$R_S \cong R_{BCS} + R_{res} \cong \frac{C}{T} \exp\left[-\frac{D}{T}\right] + R_{res}$$

Coefficient C, D and residual resistance R_{res} are found from data fit are listed in Table 2.

Table 2: Coefficients from Data Fit

Frequency [GHz]	C	D	R_{res}
0.3254	11398	19.507	5.96
0.6508	85433	20.061	11.23
0.9761	127387	19.922	30.65
1.3013	250538	20.45	38.74

Coefficient C includes factors such as temperature (T), frequency (ω), and material properties of penetration depth (λ) and energy gap (Δ) as shown following expression [2].

$$R_{BCS} \cong \frac{\mu_0^2\omega^2\lambda^3\sigma_n\Delta}{k_BT}\ln\left[\frac{C_1k_BT}{\hbar\omega}\right]\exp\left[-\frac{\Delta}{k_BT}\right]$$

Here μ_0, k_B, $\hbar$ are permeability in free space, the Boltzmann constant, and the Planck constant respectively. With given data, frequency dependence of C can be easily shown as in Figure 6. The experimental data shows $\omega^{2.17}$ while BCS theory predicted ω^2 dependence.

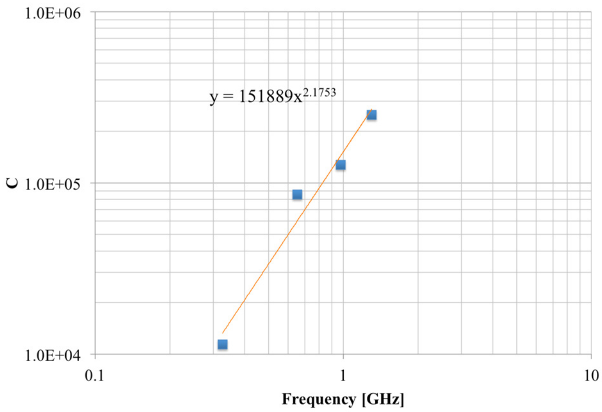

Figure 6: Frequency dependence of coefficient C.

Surface residual resistance, R_{res}, were also extracted. Then the residual resistance was plotted to see the frequency dependence as shown in Figure 7.

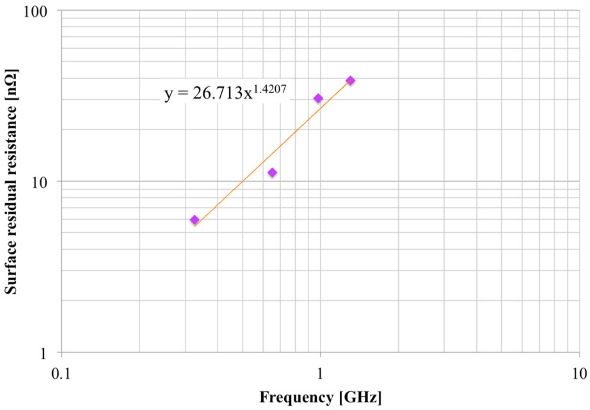

Figure 7: Residual surface resistance as a function of frequency.

The residual surface resistance does not seem to follow a strict power law dependence on the frequency. This could be indicative of a slight non-uniformity of the surface on the inner conductor. However, there is a clear trend, which will have to be investigated further both experimentally and theoretically to find the origin of this residual surface resistance.

FUTURE EXPLORATION

We plan to repeat the baseline test to make sure the test system works without error. Once the baseline is established we will repeat the test after processing the cavity with various recipes. For example, we can dope the cavity with Nitrogen and find the frequency dependence. These experimental data will be used to test new theories.

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