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INVESTIGATION OF THE SURFACE RESISTANCE OF NIOBIUM BETWEEN 325 MHz AND 1300 MHz USING A COAXIAL HALF-WAVE CAVITY*

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Abstract

The surface resistance of superconductors depends on frequency, temperature, rf field strength, and surface preparation. In particular, a low temperature bake around 100 C has been shown to modify the high-field behavior of the surface resistance. Using a coaxial half-wave resonator operating at 325, 650, 975 and 1300 MHz [1, 2] we have initiated a research program to better understand the role of low temperature heat treatment on the surface resistance of niobium.

INTRODUCTION

The well-known expressions for the surface resistance of superconductors in electromagnetic fields, and its dependence on frequency, temperature, and a few materials parameters, were obtained as a perturbation theory under the assumption that the magnitude of the electromagnetic field is much smaller than the critical field. This resulted in a surface resistance independent of the magnitude of the electromagnetic field.

There have been several attempts at developing theories of the surface resistance at high rf field, up to the critical field [3-5], but, at present, there is no universally accepted consensus on the correct fully self-consistent theory.

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). 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.

FREQUENCY DEPENDENCE

In the low-field limit the BCS surface resistance of superconductors is given by

$$R_{BCS} \cong \frac{\mu_0^2 \omega^2 \lambda^3 \sigma_n \Delta}{k_B T} \ln\left[\frac{C_1 k_B T}{h\omega}\right] \exp\left[-\frac{\Delta}{k_B T}\right] \qquad (1)$$

In real materials, however, the non-isotropy of the gap and the Fermi surface, and the smearing of the gap can produce deviations from Eq. (1).

In the past the frequency dependence of the surface resistance was usually obtained by measurements in different frequencies and, over the range of interest for particle accelerators was of the form $\omega^{1.7\to 2}$.

Not included in Eq. (1) also is the so-called residual surface resistance which includes all the sources of power dissipation that do not vanish as $T \to 0$.

Figure 1 shows the temperature dependence of the low-field surface resistance measured in the four lowest TEM modes of the half-wave cavity.

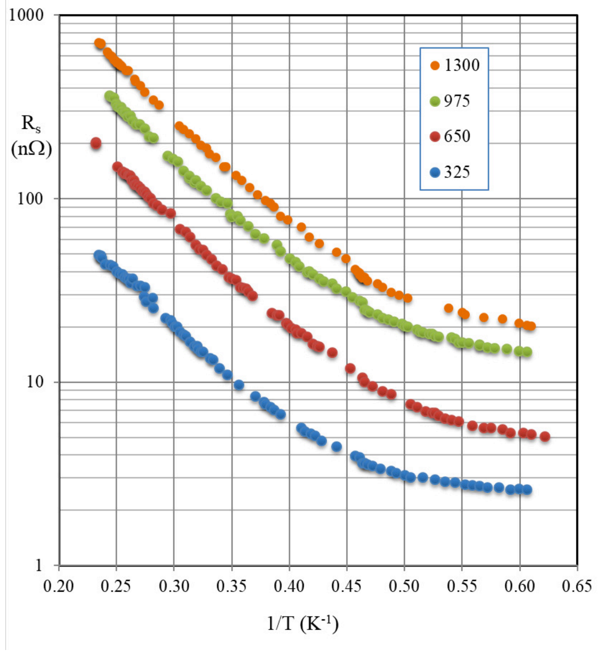

Figure 1: Temperature dependence of the low-field surface resistance of the four lowest TEM modes.

The results of Fig. 1 were obtained after the following surface preparation and treatments.

1. Post fabrication cleaning. Cleaning followed typical UHV cleaning procedure. The cavity was cleaned in a heated ultrasonic tank and triple rinsed with deionized ultra pure water.
2. Bulk BCP. Damaged niobium layer was removed by the chemical composition of HF (48%):HNO_3 (60%):H_3PO_4 (85%) = 1:1:2 inside the clean room. It was aimed to remove 150 microns but the thickness

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measurement showed the actual removal 125 micron on average. After the first test additional 50 microns were removed. Figure 2 is showing how it was set up.

Figure 2: BCP set up in the clean room.

3. Heat treatment. High temperature heat treatment was performed at 800 deg C for 2 hours. During the heat treatment elements (especially hydrogen) were monitored.
4. Light BCP. Ten micron removal performed following same set up of bulk BCP.
5. High pressure rinse.
6. Clean room assembly. Rinsed cavity was dried overnight and it was assembled with ancillary parts. The additional parts were input and pick up couplers, vacuum valve and burst disc for safety. Other ports were blanked off as shown in Fig. 3.

Figure 3: Assembled cavity taken out from clean room.

7. Cool down. The cavity was loaded in a dewar of 28 inch diameter. The initial volume of 4.3 K helium liquid was 590 liters.

The data of Fig. 1 can be fitted to the formula

$$R_s(T)=\frac{A(\omega)}{T}\exp\left[-\frac{\Delta}{kT}\right]+R_{res} \qquad (2)$$

where $A(\omega)$, Δ/k, and R_{res} are fitting parameters.

The frequency dependence of the three fitting parameters are shown in Figs. 4, 5, and 6.

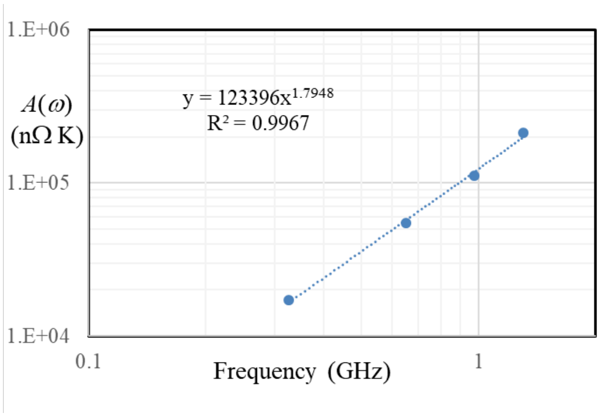

Figure 4: Fitting parameter $A(\omega)$.

In this frequency range and after the surface preparation described above the surface resistance shows a power frequency dependence ~1.8. This is different from the quadratic frequency dependence often assumed but consistent with numerical calculations.

As expected the fitting parameter Δ/k is frequency independent.

The component of the surface resistance that remains finite at T=0 displays a power frequency dependence ~1.5. This is quite different from what would be expected from trapped flux or a normal inclusion (~0.5).

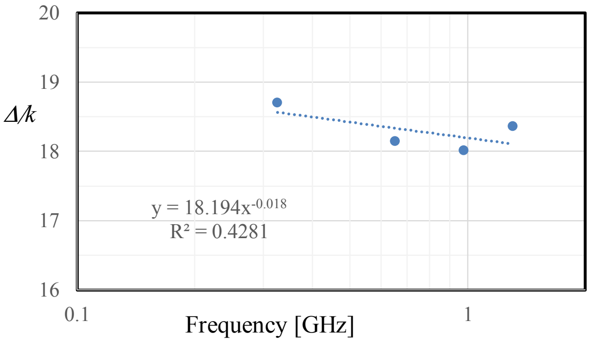

Figure 5: Fitting parameter Δ/k.

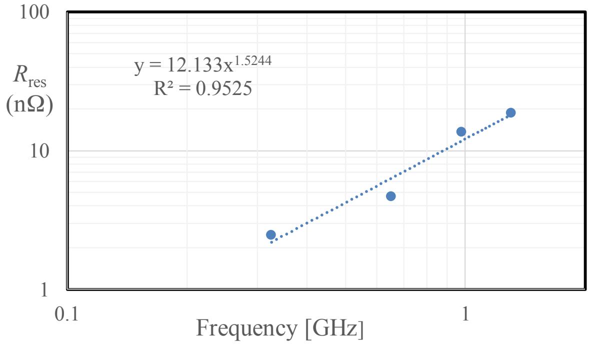

Figure 6: Fitting parameter R_{res}.

FIELD DEPENDENCE

Figure 7 shows a Q-curve as function of the peak surface magnetic field obtained at 4.35 K in the 325 MHz mode.

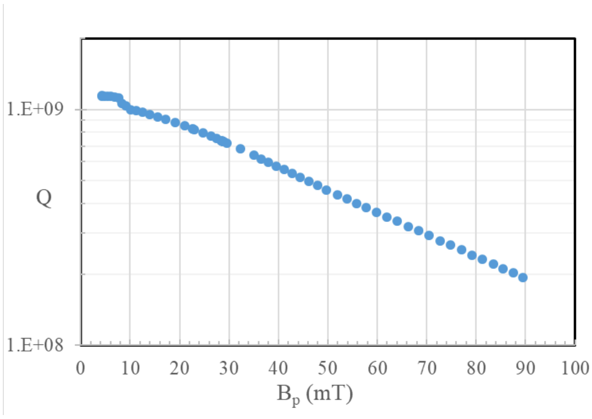

Figure 7: Q-curve at 325 MHz and 4.35 K.

From the Q-curve and the geometrical factor of 59 Ω, an average surface resistance can be obtained and shown as the blue dots in Fig. 8. Following the method described in [6], the actual field-dependent surface resistance $R_s(B)$ can be derived and is shown as the red curve.

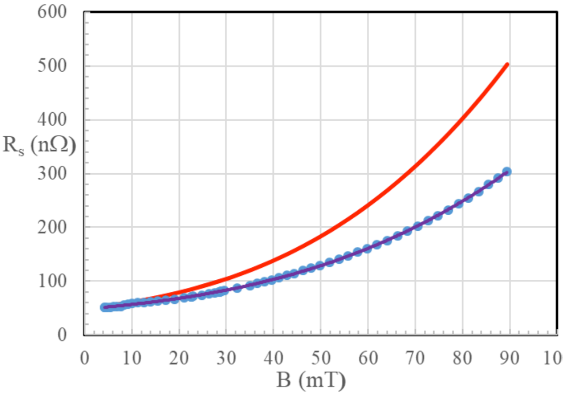

Figure 8: Average surface resistance from Fig. 5 (blue dots and purple curve) and actual surface resistance (red curve).

ON-GOING WORK AND PLANS

The results presented here are part of an investigation of the low-temperature baking (~120 C) of niobium cavities that has shown that it could reduce the high-field surface, at least at high frequency. The underlying physics is still poorly understood and by looking at the frequency dependence one may be able to shed some light on the underlying processes. The complete program involves looking at the evolution of the frequency dependence of the three fitting parameters and the field-dependence of the surface resistance after a low-temperature baking schedule of: no baking, 6 hours, 6+6 hours, 6+6+12 hours, and if warranted 6+6+12+24 hours.

After the completion of this series of tests, our plans are to repeat them following nitrogen infusion in the niobium cavity.

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