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An Eddy-current based RRR measurement technique for SRF cavities

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Abstract.

Residual Resistivity Ratio (RRR) is an important parameter which is used to determine the purity and thermal conductivity of Niobium (Nb) utilized for fabrication of Superconducting Radio Frequency (SRF) cavities. The usual 4-wire electrical resistance measurement method is destructive in nature and produces a non-local (average) measurement of the electrical conductivity. The present work utilizes Printed Circuit Board (PCB) based planar inductor as sensing element. The impedance variation of the sensing element in the presence of a conducting metal (Nb), is used to determine the conductivity of the Nb target. A generalized equation for RRR is proposed in terms of parameters 'a' and 'b' associated with the sensing coil. The measurement method is experimentally verified by utilizing samples of Nb of known RRR values. The sensor parameters ('a' and 'b') are also established for cryogenic conditions. Errors in measurement, accuracy and repeatability of measurements down to 4.2 K are reported.

1. Introduction

A Superconducting RF cavity requires a high thermal conductivity to dissipate the RF power into the surrounding liquid Helium (He) as shown in [1, 2]. This requires niobium of high purity. A Residual Resistivity Ratio (RRR) value gives a direct indication of the purity of niobium. The Residual Resistivity Ratio (RRR) is defined as the ratio of resistivity of the conductor (here Nb) at room temperature (ρ_{290K}), to the electrical conductivity just above the critical temperature ($\rho_{\sim 10K}$). It has also been shown that there exists a direct relation connecting the RRR with the thermal conductivity (λ), which at 4.2 K is given by $\lambda = \frac{RRR}{4}$. Hence, facilities which work on particle accelerators use the RRR as the first indicator for the performance of the cavity. The conventional method of determining the value of RRR measurement involves the 4-wire electrical resistance measurement (DC measurement). There are two major limitations for this method. (1) It is a destructive process in which a piece of a specified length is cut from the bulk material and is used for the RRR measurement. (2) DC measurements are non-local in nature i.e., the measured resistance indicates an average over the entire length. After the SRF cavities are fabricated, the RRR values cannot be measured. This limitation can be overcome by adopting AC measurement techniques. Few AC RRR measurement techniques have been proposed by Safa, H., et. al. and also Singer, W., & Proch, D. etc [3, 4]. But, the main drawback of the aforementioned methods is the absence of a theoretical relation between the RRR and the measured parameter.



The present work utilizes existing eddy-current principle of the measurement of electrical conductivity, applied for sniobium (or any other material) and furthermore extends it into cryogenic temperatures. The existing theoretical equations connecting the electrical conductivity and the impedance change of the sensor are modified and appropriate corrections are applied to accurately measure the electrical conductivity and the RRR at cryogenic temperature.

2. Eddy-current sensor

An eddy-current sensor primarily consists of a coil which is excited using an AC signal with a carefully adjusted frequency. It has been previously established that the current density profile induced on the conductor behaves according to equation (1).

$$\delta = \frac{1}{\sqrt{(\mu_0 \pi f \sigma)}} \quad (1)$$

where δ is the skin depth, σ is the electrical conductivity of the material, f is the frequency of the AC excitation and μ_0 is the permeability of free space. The eddy-current will penetrate deeper for less conducting materials compared to higher conducting material at the same frequency. As the temperature decreases, the electrical conductivity of the material increases from a low value to a very high value. As a result, the operating frequency also has to be reduced significantly to avoid the effect of surface non-linearities on the measurement of the electrical conductivity. There have been numerous analytical models describing the variation of the coil impedance ($Z = R + jX$), when a non-ferrous conductor is brought near it. A detailed analysis requires utilizing the concept of a normalized impedance plane as suggested by [5].

The sensor coil impedance without the presence of the target, is defined by $Z_0 = R_0 + jX_0$. When a target is brought near the sensor coil, its impedance changes to $Z_c = R_c + jX_c$. Then, the normalized components are given by $R_{cn} = \frac{R_c - R_0}{X_0}$ and $X_{cn} = \frac{X_c}{X_0}$, where $X = 2\pi f L_s$. A detailed description of how the (R_{cn}, X_{cn}) moves along the impedance plane when the reference number ($\frac{r}{\delta} = r\sqrt{(\mu_0 \pi f \sigma)}$) and the lift-off (coil-to-sample spacing) changes, is described by [5]. Here, r is the mean coil radius. The path followed by the (R_{cn}, X_{cn}) plot when the distance between the coil and the target is varied (lift-off), is along a straight line for the same frequency. The existence of a relation between the phase angle made by the lift-off curve and the electrical conductivity of the target was reported by [6]. They proposed that a linear relation exists between the cotangent of the phase angle (θ) and reference number ($\frac{r}{\delta}$). This can be used to determine the electrical conductivity of the target given by equation (2)

$$\sigma = \frac{(\cot\theta - b)^2}{\mu\pi a^2 r^2 f} \quad (2)$$

Here, the linear approximation is dependent on the sensor geometry, the electrical conductivity of the material and the frequency of operation. But, within a limited range of $\frac{r}{\delta}$, the sensor response can be modeled to be linear with a sufficient accuracy with respect to the slope of the lift-off lines even at ~ 10 K.

2.1. The Dual Slope RRR Measurement technique

In this paper, a method based on an eddy-current measurement technique is presented, which utilizes equation (3) at two different temperatures.

The modified equation for RRR based on equation (2) is given by

$$\frac{\sigma_{\sim 10K}}{\sigma_{290K}} = \frac{(\cot\theta_{\sim 10K} - b_{\sim 10K})^2}{(\cot\theta_{290K} - b_{290K})^2} \frac{a_{290K}^2}{a_{\sim 10K}^2} \frac{f_{290K}}{f_{\sim 10K}} \quad (3)$$

Here, the two slopes $\cot\theta_{290K}$ and $\cot\theta_{\sim 10K}$ are the slopes of the lift-off lines at the selected frequencies f_{290K} and $f_{\sim 10K}$. A simplified relation can be obtained by taking the slopes at the same frequency at both the temperatures ($f_{290K} = f_{\sim 10K}$). Consideration must be given regarding the optimum frequency because the penetration depth (δ) is a function of that frequency. This means that at 10 K if the frequency is too high, the effect of surface defects will predominate the changes in impedance and the measured conductivity will be erroneous.

3. Multilayer planar coil design

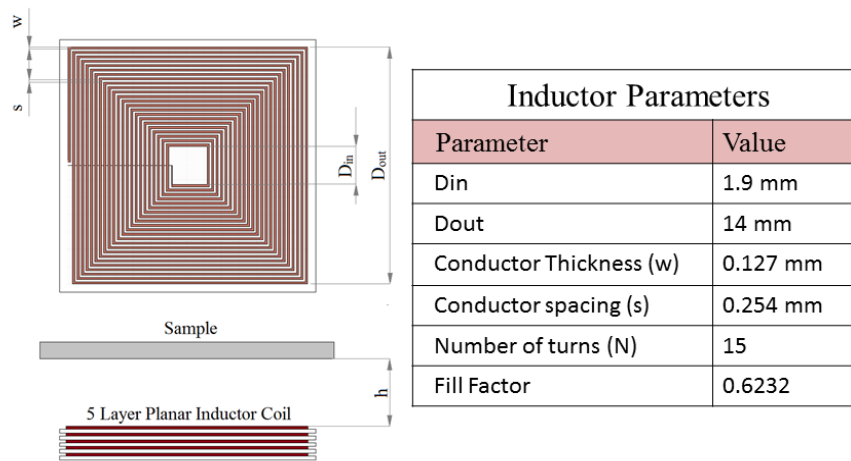


Figure 1. PCB-based multilayer planar inductor.

Two PCB-based multilayer planar inductor coils of exactly the same dimensions were used as the sensing and the reference elements for the experiment as shown in figure 2(b). One was used to provide the reference impedance Z_0 and the other, was kept in the presence of the target that provided the modified impedance Z_c . A multilayer planar inductor PCB-based coil design was chosen as this technique can be scaled down and used to produce an elaborate array of coils for a complete surface RRR mapping. It was needed to keep the dimensions of the coil as small as possible due to various considerations such as local area measurement, cryostat bore diameter etc. The other considerations are the frequency of operation and the Q-factor of the coil. Typical values of a single layer planar inductor are listed in figure 1. A detailed design consideration for a planar multilayer coil design is given by [7].

4. Experimental Procedure

Four different samples of different RRR values:- (1) 3.21 (2) 58.2 (3) 259 and (4) 367, measured by 4-wire measurement technique, were used in this experiment. Here, the samples 1, 2 and 4 were used as the calibration samples and to obtain the 'a' and 'b' sensor parameters defined in equation (3). The third one was used as an unknown sample and the conductivity as well as the RRR for this was measured using equation (3). Two measurements were done at the sampled temperature (one sample per second), one was used to measure the reference impedance Z_0 and the other, to measure the modified impedance Z_c . The sample was mounted in custom-made sample holder fabricated from a special bakelite sheet called Hylam. Initially, the sensor to target distance was kept at 0.5 mm. The impedance of the coil was acquired from 290 K to 4.1 K. This procedure was repeated for the same sample kept at different lift-off distances by varying it from 0.5 mm to 3 mm. Similarly, all the other samples were tested.

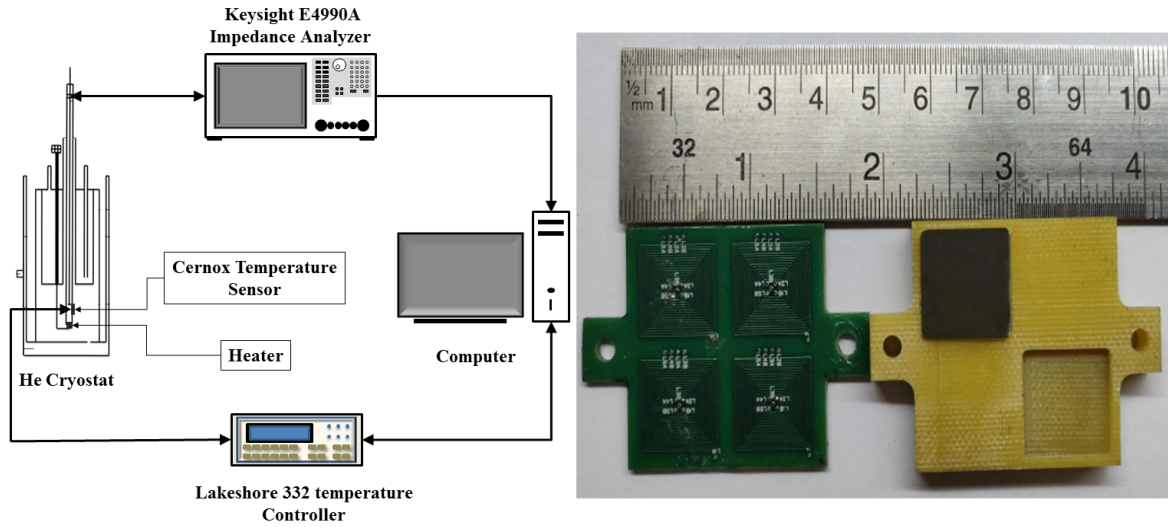


Figure 2. (a) Schematic of the measurement setup. (b) Sensing coil array with one reference and three sensing coils along with the sample holder.

Figure 2. shows the schematic for the measurement of the impedance of the planar coil in the presence of the target. An impedance analyser is used to measure the real and imaginary parts of the coil impedance at specific frequencies. The range of frequencies to sweep is carefully determined based on the thickness of the target as well as the operating temperature. A cryostat with a temperature sensor (Cernox) with a heater combination is used to maintain a stable temperature. The data was continuously acquired using a DAQ system with the help of the LabView software.

5. Procedure for determining the RRR of a sample

- (i) The L_s - R_s and L_0 - R_0 curves are determined for a range of frequencies from 1 kHz to 100 kHz initially for 290 K and then for ~ 10 K as shown in figure 3, using the experimental setup discussed in the previous section. From the value of L_s - R_s and L_0 - R_0 , R_{CN} - X_{CN} curves are obtained using the equations discussed in the section 2 and are shown in the figure 4.
- (ii) The lift-off lines represent a line connecting the R_{CN} - X_{CN} curves at different spacings of the sensing coil with reference to the target, for a given frequency of excitation. The slope of the lift-off line is a function of the electrical conductivity of the material. From the figure 4, it can be seen that the lift-off line has a higher slope at 10 K, indicating that the electrical conductivity has increased due to the decrease in the temperature. $\cot \theta_{290K}$ and $\cot \theta_{\sim 10K}$ are given by the slopes of the lift-off lines at 290 K and 10 K respectively.
- (iii) Using the $\cot \theta_{290K}$ and $\cot \theta_{\sim 10K}$ values in the equation (3), the RRR of the sample can be obtained. These slopes are then substituted in equation (2) to determine the absolute values of electrical conductivity. This is shown in Table 1. It should be noted that the coil specific parameters ($a_{\sim 10K}$, $b_{\sim 10K}$) and (a_{290K} , b_{290K}) have been determined by using 3 samples of known electrical conductivities to generate the $\cot \theta$ vs. r/δ plot as shown in figure 5.

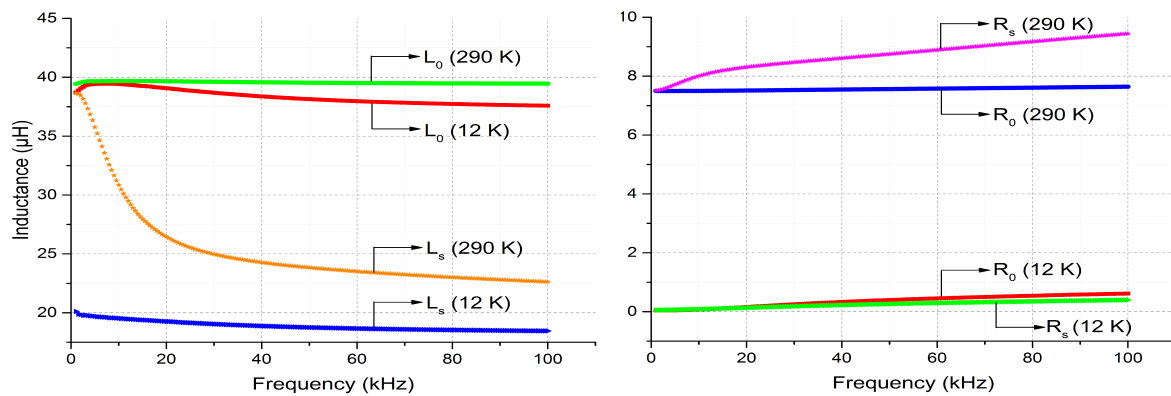


Figure 3. L_S - R_S and L_0 - R_0 curves for the unknown sample at 290 K and 12 K.

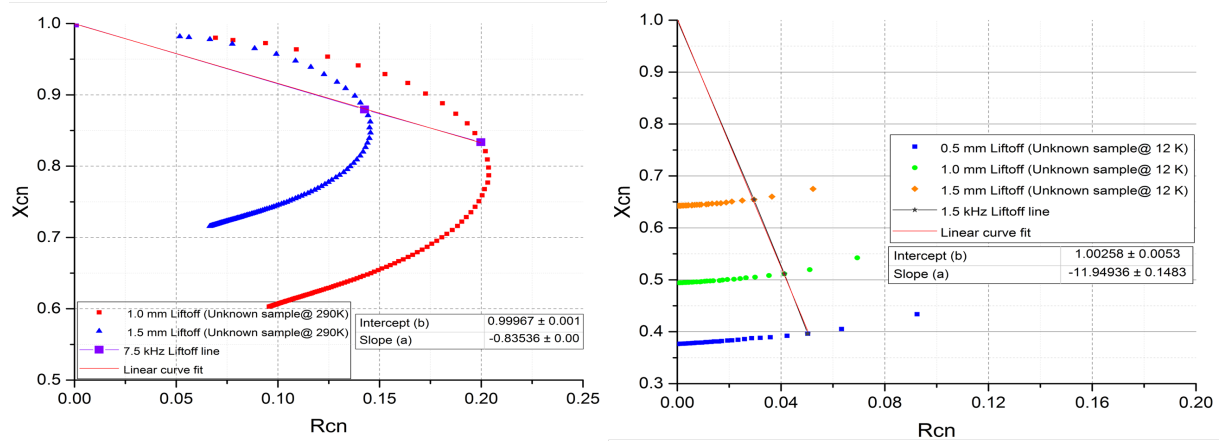


Figure 4. R_{CN} - X_{CN} curve for an unknown sample with the lift-off line for 290 K and 12 K.

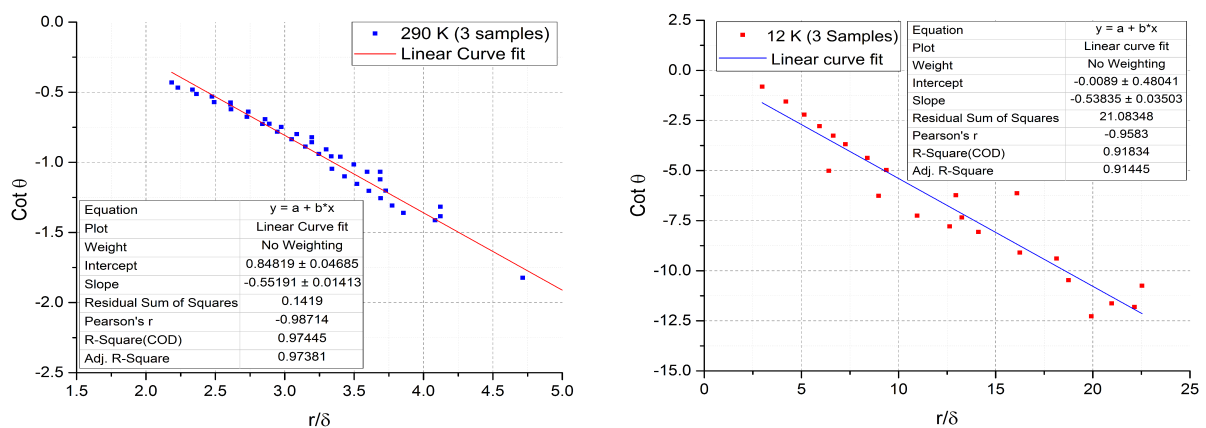


Figure 5. $\cot \theta$ vs. r/δ curves for 3 samples with different RRR at 290 K and 12 K.

6. Experimental Results

Three samples having the RRR-values of 3.21, 58.2 and 367 were used to determine the ‘a’ and ‘b’ parameters for the PCB-planar coil sensor. These parameters are mainly dependent on

Table 1. The RRR-value and electrical conductivity calculated for an unknown sample.

T	f	a	b	$\cot \theta$	σ	Measured σ	% error in σ	RRR
12 K	1.5 kHz	-0.5383	-0.0089	-11.805	1.52E+09	1.55E+09	1.75	255.3
290 K	7.5 kHz	-0.5519	0.8482	-0.8354	5.95E+06	5.96E+06	0.146	

the coil geometry and the temperature. This is done by varying the slopes of the lift-off lines over a very wide range of frequencies, as seen from figure 5. A single sample can be used to determine the ‘a’ and ‘b’ parameters, but the accuracy of measurement will be reduced. The $\frac{r}{\delta}$ was intentionally limited to a certain range for all the samples, to reduce the non-linearities due to the surface defects and fringing effects of the sensor. $\cot \theta$ follows a fairly linear trend at 290 K and at 12 K as seen from figure 4. The values of $a = -0.5519$ and $b = 0.8482$ at 290 K and $a = -0.5383$ and $b = -0.0089$ at 12 K, were then used to determine the electrical conductivity and the RRR of the unknown Nb-sample.

It should be noted that the RRR values $\gg 400$ can also be measured using the same technique by reducing the operating frequency below 1 kHz so as to limit the skin effect and therefore allowing for much deeper penetration of the currents. More samples will be tested and nonlinear effects will be studied in detail at a later point of time. Errors at ~ 10 K and lower can be associated with the lead compensations, that were employed in the measurement techniques. Fixture compensations were only done at room temperature but, as the fixture impedance varies with temperature, the errors associated with the measurement also increases.

7. Conclusion

A technique for measuring the RRR and electrical conductivity of Nb using planar multilayer inductor was tested for a sample of an unknown RRR. The method was confirmed with existing RRR measurement technique. Sensor parameters ‘a’ and ‘b’ were determined using samples of known RRR. Percentage errors of less than 1.5% at 12 K and less than 0.5% at 290 K were achieved for the electrical conductivity measurement. Larger errors at lower temperature maybe a result of poor fixture compensation at varying temperatures.

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