IOP Conf. Series: Materials Science and Engineering **1327** (2025) 012216 doi:10.1088/1757-899X/1327/1/012216

Non-Destructive Measurement of Electrical Conductivity in Thin-Film Nb coated Cu for SRF Cavities using Planar Eddy Current Sensors

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Abstract. A novel contactless method for measuring the electrical conductivity of thin-film niobium (Nb) superconductors is presented. The impedance of the planar eddy current sensors is measured with thin film Nb-coated targets and Cu-only targets. The difference in resistance ΔR is a function of the film's conductivity. Experiments identified a distinct minimum in ΔR with and without the Nb film on copper (Cu) substrates across various frequencies. Conductivity was calculated using a theoretical model. The impedance of the planar eddy current sensors was measured at room and liquid nitrogen temperatures, with Nb-coated Cu targets deposited using DC magnetron sputtering. The method observed a temperature-dependent frequency shift in minimum ΔR, indicating the conductivity changes. A Python simulation model was used to calculate the conductivity from the measured impedance data. There was a 26% difference from experimental conductivity values. This non-destructive, contactless approach offers a promising means to assess thin-film superconductor conductivity.

1 Introduction

The key component of a particle accelerator is the superconducting radio frequency (SRF) cavities. SRF cavities allows for efficient acceleration of particles with minimal energy loss. Traditionally, SRF cavities have relied on bulk niobium (Nb) for its exceptional superconducting properties, but localized defects in bulk Nb can cause energy absorption and quenching, significantly hindering performance. In addition, bulk Nb requires a significant amount of material, which can be expensive and limit its use in large-scale accelerators. Researchers are exploring thin films of Nb deposited on copper (Cu) substrates as a promising alternative to bulk Nb cavities [1, 2, 3]. These thin films offer several advantages, such as high thermal conductivity, high critical fields, and reduced Nb usage. Because of its high thermal conductivity, the copper substrate allows for efficient heat dissipation, which is essential for maintaining superconductivity. Compared with bulk Nb cavities, thin films require significantly less Nb material, making them more cost-effective and resource-efficient.

To ensure the optimal performance of thin-film Nb cavities, it's crucial to assess the purity of the Nb layer. A key parameter for this evaluation is the Residual Resistance Ratio (RRR)[4, 5]. The RRR is calculated by dividing the resistivity at Room temperature by the resistivity at a temperature below the critical temperature[5]. Higher RRR values indicate higher purity and, consequently, better superconducting properties. However, traditional methods for measuring RRR, like 4-probe DC [6], are unsuitable for delicate thin films. These methods require physical contact with the sample, which can damage the film. A solution to such a problem is to replace it with nondestructive methods.

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This study introduces a novel approach for measuring thin-film Nb superconductors' electrical conductivity (and hence RRR) using planar eddy current sensors. These sensors interact with the sample without physical contact, making them ideal for delicate thin films. The method relies on the principle of eddy currents. The study in this paper uses the difference in resistance(ΔR) of the coil in the presence of the target with and without the Nb film on Cu at various frequencies. This difference is correlated to the conductivity of the coating and the layer thickness. In order to verify the theory, experiments were conducted at room and liquid nitrogen temperatures(77K). A minimum value of ΔR with frequency from the experiments conducted was observed to be a function of the layer conductivity. From a well-established theoretical model described by [7], the conductivity of the Nb film was determined from the experimental data.

2 Principle of Operation

An eddy current sensor consists of a coil and a conductor. The coil carries an alternating electric current, which creates a constantly changing magnetic field around it. Figure 1 illustrates the basic setup for the problems studied in this paper. A planar coil with a rectangular cross-section is the sensor. This coil is positioned in the air, with its center line perpendicular to the target. The target is a thin film Nb coated on a bulk Cu layer. The conductivity of thin film Nb is denoted by σ_1 and the conductivity of the bulk Cu layer is denoted by σ_2. The top layer has a known thickness (d) of the order of μm, and the bottom layer thickness is much larger than d. The coil is held at a height (h_1) above the target. The coil has n number of turns, inner radius, r_1, the outer radius r_2, and the thickness of the coil L is calculated as L = h_2 - h_1 where is h_2 is the distance of the target from the top layer of the coil.

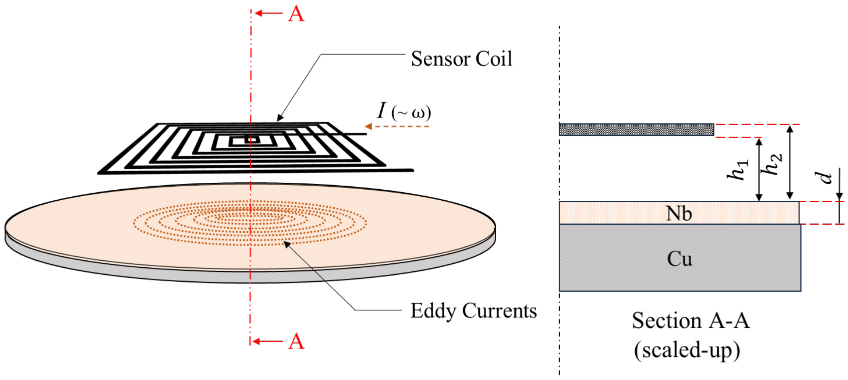

Figure 1: Coil and the target

The relation between the impedance (Z) of the coil, conductivities σ_1 and σ_2 and all the associated dimensional parameters is derived by the forward problem defined by Dodd and Deed [8] and is given as,

$$Z = Kj\omega \int_0^\infty \frac{I^2(\alpha, r_1, r_2)}{\alpha^5} \left(2L + \frac{1}{\alpha}\left[2e^{-\alpha L} - 2 + A(\alpha)\phi(\alpha)\right]\right) d\alpha \tag{1}$$

$$K = \frac{\pi \mu_0 n^2}{L^2 (r_2 - r_1)^2} \tag{2}$$

$$I(\alpha, r_1, r_2) = \int_{\alpha r_1}^{\alpha r_2} x J_1(x) dx \tag{3}$$

$$A(\alpha) = e^{-2\alpha h_2} + e^{-2\alpha h_1} - 2e^{-\alpha(h_1+h_2)} \tag{4}$$

$$\phi(\alpha) = \frac{(\alpha+\alpha_1)(\alpha-\alpha_2) + (\alpha-\alpha_1)(\alpha_1+\alpha_2)e^{2d\alpha_1}}{(\alpha-\alpha_1)(\alpha_1-\alpha_2) + (\alpha+\alpha_1)(\alpha_1+\alpha_2)e^{2d\alpha_1}} \tag{5}$$

and

$$\alpha_{1,2} = \sqrt{\alpha^2 + j\omega\mu_0\sigma_{1,2}} \tag{6}$$

Here, K is a coil constant, μ_0 is the permeability of free space $I((\alpha, r_1, r_2)$ is the current, J_1 is the first order vessel function, α denotes the spatial wave vector. $A(\alpha)$, $\phi(\alpha)$ and $\alpha_{1,2}$ are functions of α and ω is the angular frequency of the excitation current. John C Moulder showed in [7] that the conductivity and thickness of the coating can be determined if the impedance information is available for different frequencies. This was extended to show that the difference between the impedances of the sensor in the presence of the bulk substrate Z_{NC} and the coated substrate Z_C denoted as Δ Z given by

$$\Delta Z = -\Delta\sigma K\mu_0\omega^2 \int_0^\infty \frac{I^2\left(\alpha, r_1, r_2\right)}{\alpha^6} A(\alpha) \frac{1 - e^{-2d\alpha_2}}{\alpha_2(\alpha + \alpha_2)^2} d\alpha \tag{7}$$

These equations are formulated for 3D coils with either an air core or an iron core. For planar geometries, a dimensionless correction factor must be introduced to account for the 2D nature of the coil. In this study, the correction factor incorporated in the term K is given by $\frac{r_2}{r_1}$. The impedance of the sensing coil was measured both with and without the thin film. Using these measurements, the change in resistance (ΔR), which corresponds to the real component of ΔZ, was calculated. The variation of ΔR with frequency was observed to depend on the thin film's conductivity and layer thickness. The electrical conductivity of the thin film was determined from the minimum value in the ΔR vs. Frequency plot.

3 Experiment Procedure

In order to verify the theory presented above, experiments were carried out at 300K and 77K. A planar inductor of dimensions shown in table 1 was designed and fabricated. Impedance of the sensing coil was obtained with a thin film Nb coated on a Cu substrate prepared using DC magnetron sputtering as target as well as one with bare Cu. From the impedance data, the resistance change (ΔR) was determined. A Python model was created to compute the inverse problem and to reverse calculate the conductivity of the thin film from the impedance data.

Table 1: Inductor Parameters

Parameter	**Dimensions**
Turns (n)	53
Din	1.84 mm
Dout	28.764 mm
Conductor Thickness (w)	0.127 mm
Conductor spacing (s)	0.127 mm

3.1 Preparation of Target

A 0.55 mm-thick OFC sheet served as the substrate for the deposition of a thin film of Nb, achieved through Direct Current (DC) Magnetron sputtering using the HHV Auto 500 Instrument. For sputtering purposes, a 99.99% pure 2-inch Nb target was used. The coated target is as shown in figure 2. The sputtering parameters employed for the coating through DC magnetron sputtering are detailed in table 2. In addition to the copper target, a glass slide was introduced into the chamber under identical coating conditions to coat Nb of equivalent thickness. This step helped measure the conductivity of the thin film Nb after the coating process.

3.2 Conductivity measurement of the thin film Nb coated using Four Probe Measurement

The electrical conductivity of the coated Nb sample was measured using the conventional four-probe method. The conductivity of the thin film was measured using the thin film that was coated on the glass slide. The schematic of the measurement setup is shown in figure 3.

The measured values of the electrical conductivity of the thin film Nb-coated glass slide are presented in table 3.

The table shows the target's conductivity having three thicknesses, namely, 300 nm, 350 nm, and 400 nm, which are named target 1, target 2, and target 3, respectively. The conductivity for these targets was measured at room temperature and 77K. The electrical conductivity increased from 2.80×10^5 at room temperature to 4.72×10^5 at 77K for target 1 and so on, as shown in Table 3.

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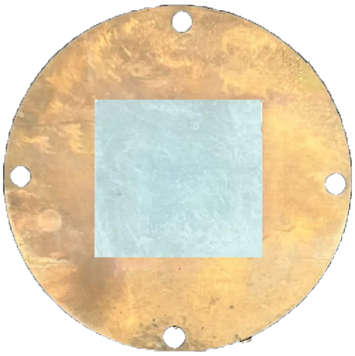


Figure 2: Thin film Nb coated on Cu substrate

Table 2: Sputtering parameters

Power	100 W
Base Pressure	2.2×10^{-5} mbar
Working Pressure	2.3×10^{-3} mbar
Argon Pressure	50 mbar

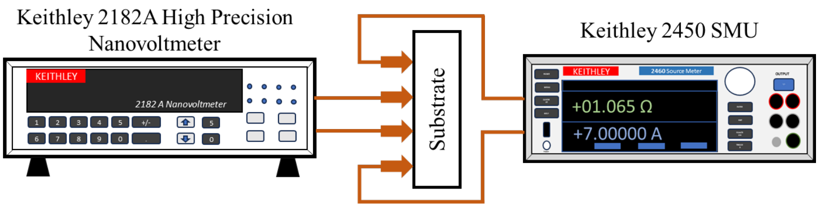


Figure 3: 4-Probe measurement schematic

Table 3: Conductivity of the two coated targets measured using the Four Probe

Thickness of the sample coated (nm)	Electrical conductivity at Room Temperature (S/m)	Electrical conductivity at Cryogenic Temperature (S/m)
300 (Target 1)	2.80×10^5	4.72×10^5
350 (Target 2)	3.20×10^5	4.68×10^5
400 (Target 3)	3.53×10^5	4.66×10^5

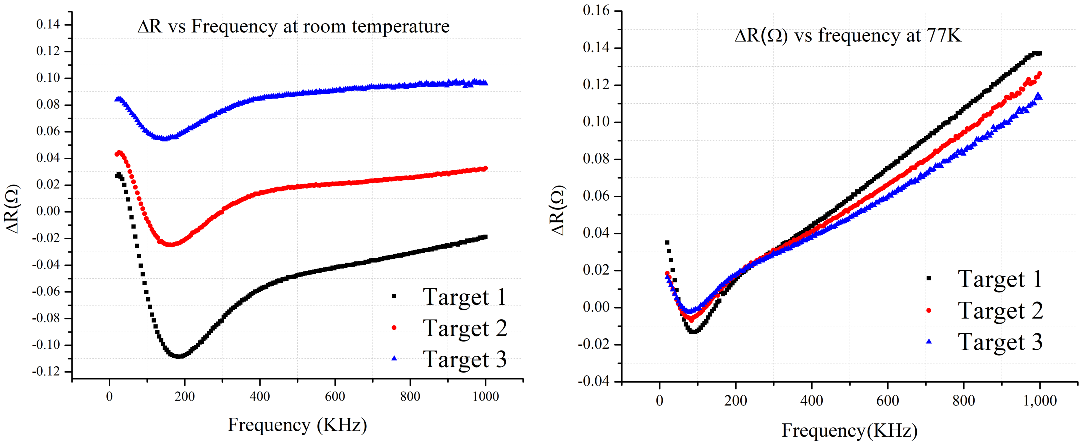
3.3 Noncontact measurement using Eddy current sensors

The experiment was carried out to determine ΔR in various frequency ranges to identify the range at which the minimum was observed. The distance between the sensor and the target was varied for both samples using nylon washers. Measurements were taken at room temperature and 77K using an IM 3570 impedance analyzer. The measurement at 77K was made by dipping the sensor target assembly into liquid nitrogen. The frequency range for measurements was set between 100 kHz and 1 MHz.

4 Results and Discussion

The ΔR values obtained from the sensor in the presence of Cu targets coated with Nb at room temperature and 77 K are shown in Figure 4. The analysis of the experimental data aligns with the model described by [7]. The minimum values of ΔR were observed at an average frequency of 198 kHz at room temperature and 78 kHz at 77 K, calculated as the mean across the three targets. These values represent the averaged behavior and are not specific to any single target. A comparison of ΔR at these temperatures shows a decrease in the frequency at which the minima occurred for ΔR when the target was cooled to 77 K. This trend was verified at different lift-off distances, with the results for three lift-off distances (as listed for target 2 in Table 3) shown in Figure 4. On average, the shift in frequency at 77 K compared to room temperature was found to be 120 kHz.

A slight shift in the minimum frequency with varying thickness can be attributed to changes in the conductivity of the different thin films, as shown in table 3.

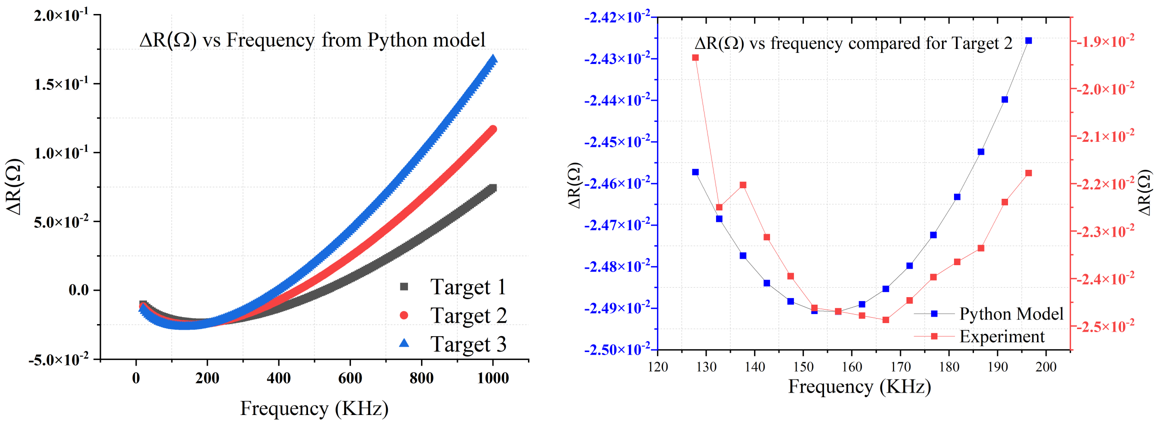


(a) (b)

Figure 4: Δ R vs Frequency at (a) Room Temperature (b) 77 K

4.1 Comparison with the Mathematical model solved using Python

Equation 7 was implemented in Python, and using the experimental values of ΔR, the conductivity of the thin-film Nb was calculated for different targets. After incorporating a correction factor into the Python model, the results were plotted as shown in Figure 5. To calculate the conductivity σ_1, the smallest ΔR from the experiment and its corresponding frequency were substituted into the real part of ΔZ in Equation 7. The Python model's calculated conductivities based on the experimental impedance data are presented in Table 4. These results were compared with the experimentally measured conductivities, revealing a discrepancy of approximately 26%. The comparison between the Python model and experimental results



(a) (b)

Figure 5: Δ R vs. Frequency with (a) Python model (b) Comparison with experimental data for Target2

shows a consistent difference of about 26%, with the model predicting lower conductivity values in all cases. The minimum frequency values predicted by the model are close to the experimental values but not identical (e.g., 176 kHz vs. 181 kHz for Target 1). This indicates that the model captures the general trend but may miss some details due to simplifications or assumptions. The consistent underestimation suggests that the correction factor or model parameters may need further refinement. Some of the difference could also come from experimental uncertainties, such as small errors in measuring ΔR or frequency. Despite this, the model reliably reflects the overall behavior of thin-film Nb conductivity and aligns well with experimental trends.

Target number	Min Frequency from Experiment	Min Frequency from Python model	Conductivity from experiment	Conductivity from Python model
1	181 KHz	176 KHz	2.80 x 10^5 (S/m)	1.83 x 10^5 (S/m)
2	167 KHz	157 KHz	3.2 x 10^5 (S/m)	2.4 x 10^5 (S/m)
3	145 KHz	147 KHz	3.53 x 10^5 (S/m)	2.8 x 10^5 (S/m)

Table 4: Experimental and Python model results compared

5 Conclusion

This study presents a novel, non-contact method for measuring the electrical conductivity of thin-film niobium (Nb) superconductors using planar eddy current sensors, offering a reliable approach for evaluating their Residual Resistivity Ratio (RRR). These sensors, well-suited for delicate films, induce eddy currents in the Nb layer, leading to measurable changes in the coil's impedance—particularly its resistive component—which directly correlates with the film's conductivity and quality. Experimental data revealed a distinct minimum in resistance difference (ΔR) between measurements with and without the Nb film on copper substrates, varying with frequency. Additionally, the minimum frequency of ΔR demonstrated a temperature-dependent shift, consistent across different film thicknesses and sensor-target distances. Conductivity values were derived from experimental impedance data using a theoretical model at both room and liquid nitrogen temperatures. A Python-simulated model predicted conductivity with a 26% difference from experimental values. While the model slightly undervalued the conductivity, it effectively captured the overall trends, showcasing its potential for application in thin-film characterization and emphasizing the need for further refinement to improve accuracy.

ACKNOWLEDGEMENTS

Author would like to acknowledge the funding from the Science and Engineering Research Board, Government of India, for undertaking the research under the scheme Core Research Grant(Reference Grant No. CRG/2021/000398).

Our thanks also go to the Indian Cryogenic Council for partially funding our attendance at ICEC 29/ICMC 2024.

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