HIGH RESOLUTION SURFACE RESISTANCE STUDIES*

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Abstract

CERNs Quadrupole Resonator enables sub-nΩ-resolution measurements of the surface resistance. Much more information about the RF performance is accessible compared to regular cavity measurements. In this contribution we show that the surface resistance decreases for low cooling rates. The design of the Quadrupole Resonator allows us to exclude the formation of niobium hydrides, the efficacy of the magnetic shielding and thermal currents as possible causes. We find that the expulsion of the residual ambient magnetic field as the cause of the reduction of the surface resistance is consistent with our results.

INTRODUCTION

The attempt to reach quality factors beyond 10^{11} and pushing the accelerating gradients of SRF cavities to the theoretical limit, the treatment dependent loss mechanisms in niobium need better understanding. The Quadrupole Resonator displayed in Figure 1 has been designed and built in 1997 to measure the surface resistance of superconducting samples at 400 MHz [1].

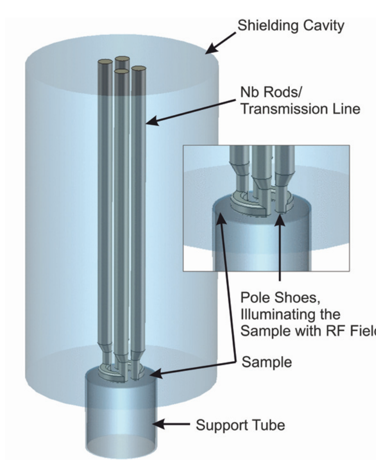

Figure 1: The Quadrupole Resonator.

In 2009 it was refurbished to extend its range to 800 and 1200 MHz [2]. Its wide parameter range was used to test theoretical surface resistance models [3]. Its capability to measure the surface resistance with a sub-nΩ-resolution at magnetic fields up to 60 mT makes it the perfect tool to test materials for continuous wave (CW) application of superconducting cavities and reveal the relevant loss mechanisms. Recently the Quadrupole Resonator has been further extended to study the influence of trapped magnetic flux on the surface resistance. In this paper the calorimetric measurement technique is reviewed and the accuracy, resolution and reproducibility of the measurements with the recently installed high precision power meters and pressure regulation system are discussed. The high resolution of the setup provides the basis for the investigation of the relation between cooling rate and surface resistance.

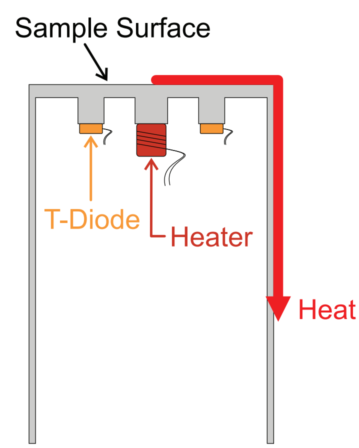

Figure 2: The thermometry chamber: Four radially symmetric temperature diodes and a DC heater are attached to the bottom side of the sample.

PERFORMANCE ANALYSIS OF THE QUADRUPOLE REONATOR

The measurement principle relies on a calorimetric technique [3]. The sample is equipped with a DC heater in the center and four temperature diodes at the high RF field region as sketched in Figure 2. Figure 3 displays how the dissipated RF power is compensated by DC heating: Starting from the temperature of the helium bath T_{bath} the sample is warmed up to a temperature of interest T_{interest} by using a DC heater attached to the bottom side of the sample. The required DC heater power is P_{dc1}. Then, the RF is switched on and the sample temperature rises due to dissipation. The heater power is then reduced to bring the sample back to the temperature of interest. The power dissipated in the sample P_{RF} is the difference in heater power with and without RF and is proportional to the surface resistance R_S:

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$$R_S = \frac{2 \cdot (P_{DC1} - P_{DC2})}{\int_{Sample} \left|\vec{H}\right|^2 dS}. \quad (1)$$

The integrated magnetic field $\left|\vec{H}\right|^2$ over the sample surface S is directly proportional to the transmitted power P_t with a factor derived by simulation and RF calibration [3].

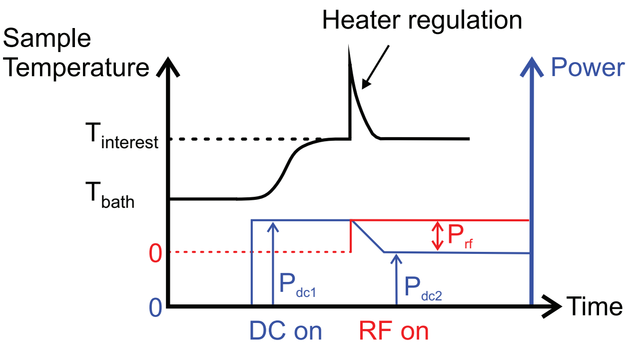

Figure 3: The Calorimetric Technique: The dissipated power P_{RF} is compensated with a DC heater.

Errors and Resolution

To date, a severe limitation of the setup has been fluctuations in the helium bath pressure of about $1-2$ mbar. The cryostat was thus equipped with a pressure regulating system, stabilizing the bath pressure to ± 0.02 mbar. The measurment errors are now dominated by the accuracy of the voltmeter (measuring the DC power) and the power meter (measuring P_t. For the error of the surface resistance, two contributions have to be taken into account: For the measurement of the heater power, the heater voltage is measured with a 6.5 digit multimeter while the resistance of 1 kΩ is known. For a stabilzed temperature (± 0.1 mK), the heater voltage changes within 10 µV. This is only relevant for low temperatures (< 2.5 K) and measurements at low RF fields (< 10 mT) since the total heater voltage is small compared to the uncertainty of the RF measurement.

The transmitted power is measured with a *Rhode&Schwarz*®NRP-Z81 power sensor. The data sheet [4] specifies the absulte error of 3.0 % which is the dominant error contribution for the surface resistance.
The temperature is measured with four temperature diodes with a specified resolution of 0.1 mK and an absolute error of 12 mK. These values are sufficiently small so that they can be neglected.

Figure 4 shows as an example the reproducibility of a measurement. The surface resistance of a reactor grade niobium sample after 48 h mild baking was measured as a function of RF field at 800 MHz and 2 K. The surface resistance at about 13 mT was taken three times. The plot shows that the reproducibility is well within the absolute uncertainty of 3 %.

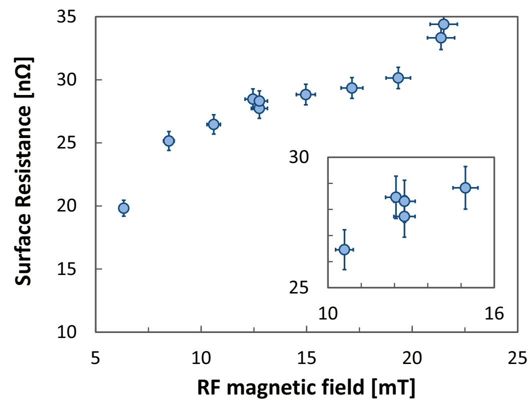

Figure 4: Reproducibility of measurements.

For the estimation of the resolution, i.e. the smallest change in surface resistance, we have to account for the minimal power needed to change the temperature of the sample by 0.1 mK. At 400 MHz, 2 K and 5 mT, this minimal heating was measured to require 2.5 µW which results in

$$R_{resolution} = 0.44\,\mathrm{n\Omega}.$$

For higher RF fields this value is decreasing quadratically due to the magnetic field dependence of the surface resistance.

As shown in this section, the Quadrupole Resonator is suitable for precise high resolution measurements which are crucial for the analysis of losses of superconductors, especially for low loss applications like CW operation.

THE INFLUENCE OF THE COOLING RATE ON THE SURFACE RESISTANCE

It has been shown that the quality factor Q ($\sim 1/R_S$) of a cavity can be reduced by thermal cycling above the transition temperature T_c [5-7]. Moreover, it was found that the effect is reversible when cooling down in the usual manner. But as the cavity cryostats are not designed for thermal cycling, it is difficult to identify the source the effect of this procedure. The Quadrupole Resonator setup with its high precision and easily controllable sample temperature enables us to study the effect of the cooling conditions on the surface resistance.

We performed a set of surface resistance measurements by changing only the cooling conditions of a mild baked reactor grade niobium sample. Specifically, by using the DC heater the sample was warmed up to 10.9 K, i.e. to the normal conducting state. In the following, the heater power was varied in the range from 0 % to 60 % of the maximum DC power $P_{dc,max} = 1$ W to slow down the transition to the superconducting state. The surface resistance was then measured at 400 MHz, 2.5 K and 15 mT. The sample temperature was monitored as a function of time by the

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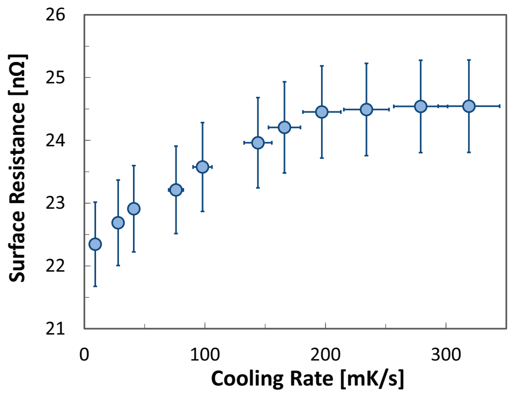

Figure 5: The surface resistance as a functiong of cooling rate.

temperature diodes and the cooling rate was derived from the cooling speed at T_c at the temperature diode position. The outcome is displayed in Figure 5. It can be seen that the surface resistance decreases significantly when cooling down slowly but saturates for fast cooling. In addition, this effect was found to be reversible.

DISCUSSION

Different sources could possibly explain the reduction of the surface resistance with slower cooling which we will dicuss in the following.

Magnetic Shielding

For cavity measurements the temperature dependence of the magnetic shielding was originally thought to be the cause of additional trapped flux. In [5] it was already shown that this is not the case. In the case of the Quadrupole Resonator only the sample is warmed up while the host cavity, cryostat and magnetic shield stay at the same temperature. Hence, we can rule out any influence of the magnetic shielding.

Niobium Hydrides

When cycling a cavity, temperatures might rise above 50 K and reach therefore the temperature range where niobium hydrides form. It is known that these hydrides affect the superconducting properties, causing the so-calld Q-disease [8]. As mentioned above, in our setup only the sample is warmed up to $\approx$ 11 K. The sample is far away from the Q-disease region while the rest of the setup stays at the helium bath temperature of less then 2 K. Niobium hydrides can therefore not be the cause.

Magnetic Field of the Heater

It could be argued that the change in surface resistance is due to the fact that the DC heater produces an additional magnetic field which partly compensates the incompletely shielded earth magnetic field (about 2 µT). Scaling the effect of trapped flux on the surface resistance from 1.3 GHz to 400 MHz under the assumption of the normal skin effect and an homogeneous magnetic field [9], we find

$$R_{\text{trapped flux}} = 3.5\,\text{n}\Omega \cdot \sqrt{\frac{400\,\text{MHz}}{1300\,\text{MHz}}} \approx 2\,\text{n}\Omega$$

which gives the right order of magnitude. To test this hypothesis, we reverse the heater current and repeat the measurements. The field produced by the heater should now not compensate but add to the ambient field and the surface resistance should increase with lower cooling rates. This is not what was observed; the progression shown in Figure 5 was reproduced. As a consequence, an additional field of the heater can be ruled out as a possible cause.

Thermal Currents

The temperature distribution over the sample surface is different for every cooling condition, i.e. for cooling down under the influence of different heater powers the local temperature gradient between the center and the outer edge of the sample changes. A local temperature gradient results in a thermo-voltage (*Seebeck effect* [10]) and in a current flow in case of a closed current circuit. These thermal currents can produce magnetic field which can be trapped, as shown in [6, 11]. In our case, the current circuit is not closed so that a thermo-voltage arises, but without current flowing. Accordingly, no additional magnetic field can be produced or even be trapped.

Expulsion of Trapped Flux

Experiments performed on isothermal niobium samples [11] and a quasi-isothermal niobium rod [7, 12] showed already that the amount of trapped flux can depend on the cooling rate. The fact that no dependence for the finegrain samples in [11] was found is likely to be an geometric effect due to a large demagnitization factor. For the niobium rod was observed that the slower the rod was cooled down the more ambient magnetic field was expelled. Our measurements complement these findings, connecting the expulsion of the magnetic field with an decreasing surface resistance.

CONCLUSION

The thermal decoupling of the sample from the host cavity and the high resolution of the Quadrupole Resonator allowed us to investigate the influence of the cooling rate on the surface resistance of a niobium sample in detail. It was found that the surface resistance decreases with slower cooling rates. This result is complementary to recent findings that an ambient magnetic field is better expelled if the cooling procedure is sufficiently slow. Hence, the expulsion of an ambient field could be linked to the decline of the surface resistance while in the case of the Quadrupole Resonator all other possible explanations could be ruled out.

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OUTLOOK

The Quadrupole Resonator has been extended with a small coil inside the thermometry chamber to create an ambient DC magnetic field on the sample. This coil has been commissioned [13] and will be used to continue the trapped flux studies in combination with the effect of the cooling rate. The idea is to cool down in different ambient fields and quantify the influence of the cooling rate on the surface resistance. In addition, these studies can be transfered to new materials and niobium films.

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