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IMPROVEMENTS TO THE CORNELL SAMPLE HOST SYSTEM*

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Abstract

RF characterization of arbitrary superconducting samples has been of interest for many years but, due to the experimental complexities, has never been achieved to its full potential. A TE mode niobium sample host cavity has been used at Cornell to characterize the RF performance of 5" (12.7 cm) diameter sample plates. It was designed and built in 2012 – 2013 and since then has encountered a range of problems. The focus of this work is to highlight these and to present solutions to assist future researchers hoping to design novel RF characterization instruments. Topics covered include coupler design, cryostat support structure, sample preparation, and a discussion of potential systematic errors introduced by the data extraction and calibration methods applied to this device.

INTRODUCTION

A system capable of measuring microwave surface resistance of flat superconducting samples up to magnetic fields $\geq$ 100mT with a resolution $<$ 1 nΩ is of great interest to the SRF cavity accelerator community. Such a device would enable the study of semi-exotic materials that have properties that would theoretically allow them to surpass the standard niobium accelerating cavities in terms of dissipation and maximum magnetic field in which the Meissner state is maintained. Depositing these materials on the curved surface of a standard SRF resonator would involve specialized equipment, research, and development but can be obtained on a flat surface using standard equipment and techniques.

Within the accelerator community, one successful measurement system is based on quadrupole resonators. [1, 2]. They have the advantages of being able to measure the sample at a relatively independent temperature from the host resonator and using a very high resolution calorimetric measurement to obtain the dissipation of only the sample instead of having to rely on calibration measurements. The negative aspects are that they currently are unable to measure completely flat samples, and the uneven heating of the sample leads to the requirement of pulsed measurements for high fields. Reported surface resistance can be impacted by the pulse shape.

A simpler sample host resonator is used at Cornell which is the topic of this paper. It measures surface resistance via monitoring the decay of energy in the resonator which has the disadvantages of thermal coupling between the host cavity and the sample and of requiring a calibration measurement to isolate the surface resistance of the sample. Its advantages are that it can achieve similar fields to the highest seen on quadrupole resonators in continuous wave operation and it can accept truly flat samples.

Despite the advantages of quadrupole resonators, many labs have expressed interest in building similar host cavities to that of Cornell. The purpose of this paper is to describe key issues that can limit its capabilities so that these labs can guide their designs appropriately.

APPARATUS

The sample host cavity shown in Fig. 1 discussed in this paper is a modified niobium pillbox designed to maximize achievable sample field when limited by thermal quench and is theoretically capable of reaching up to 120 mT when operated in a 4 GHz TE_{011}-like mode [3]. In practice the maximum field achieved before quench is $\sim$ 80 mT. The cavity could theoretically support measurements at a 5.2 GHz TE_{012}-like mode but attempts have not succeeded due to problems with the phase-locked loop. TE_{0nl} monopole modes are ideal for sample host cavities because the currents on the sample plate and host cavity flow azimuthally which reduces the danger of losses on the joint (indium gasket) between the cavity and sample plate [4].

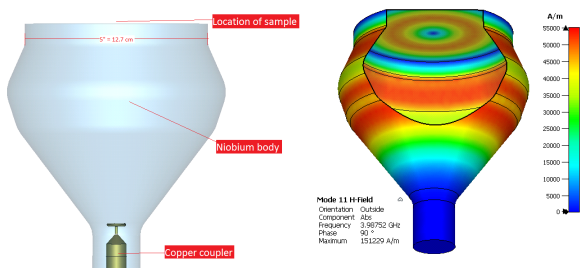

Figure 1: (Left) Cross-sectional cartoon showing how a 5" diameter sample disk is placed on the specialized Nb host cavity over an indium gasket and the location of a copper coupling antenna. (Right) The magnetic field strength of the 4 GHz TE_{011} mode indicated by color is shown on the surfaces of the host cavity and sample plate via a cut-away view.

The preparation of the host cavity follows standard procedures:

1. Electropolish with normal recipe. The electrode is a thin cylinder and could cause uneven etching/polishing due to the difference in electrode-cavity distance along the cavity.
2. High-pressure rinse with DI water
3. 800 °C out-gassing bake in vacuum for 5 hours
4. 120 °C bake in vacuum for 48 hours to reduce the surface mean free path

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5. High-pressure rinse with DI water

Low mean free path niobium is used in the RF surface penetration layer because it has a lower surface resistance than clean niobium and has empirically been shown to reduce high field Q-slope effects [5] which allows for reaching higher peak fields and could increase sample surface resistance resolution.

MEASUREMENT

The measurement is typical for high quality factor resonators. The first step is driving the cavity near resonance with a phase-locked loop. The Cornell system is unique as it uses the reflected power signal for this purpose. After allowing sufficient time for energy stored in the cavity to reach a maximum the power going into (P_f) and being reflected from (P_r) the cavity are measured. The power is then turned off and the power being emitted (P_e) from the cavity immediately after shutdown is measured along with a trace of the decay in emitted power corresponding to energy in the resonator decreasing as power is dissipated. Because of the field dependence of the surface resistance this decay is often non-exponential which makes obtaining a characteristic decay rate a source of potential uncertainty. To account for this an exponential fit is performed on a range of points where the resonator has energy $\geq (0.85)^2$ of its initial value corresponding to a field within 15% of the reported field that is calculated from the maximum energy. A range of exponential decay constants are obtained by individually fitting the trace including data points from the first point of the decay to a corresponding range of second points. The reported decay constant and its uncertainty are then taken to be the mean and standard deviation of this selection.

A concern has been that the quality of the lock onto reflected power was not correctly driving the resonator. It has been shown that the lock is sufficient and keeps the drive frequency within half of the bandwidth by a novel analysis for the conversion of the measurements into quality factor and magnetic field that accounts for the distance of the drive frequency (f) from the resonant frequency (f_0). The analysis is a modification of the standard procedure (see [6]) but omitting the assumption that $\delta = 0$ where,

$$\delta = \frac{f}{f_0} - \frac{f_0}{f}$$

and assuming that the two measurements for the coupling factor (β) are equal up to measurement uncertainty. Carrying out the analysis yields

$$\beta = \frac{P_e}{P_r + P_f}$$

The distance between the drive frequency and resonance can now be measured to determine the quality of the phase-locked loop

$$\delta = \frac{1}{\omega\tau}\sqrt{\frac{4\beta^2}{\frac{P_e}{P_f}(\beta+1)^2} - 1}$$

The quality factor is the standard expression $Q_0 = \omega\tau(1+\beta)$ and the energy stored in the cavity becomes

$$U = P_f\left(\frac{4\beta}{(\beta+1)^2 + Q_0^2\delta^2}\right)\frac{Q_0}{\omega}$$

Magnetic field on the sample is obtained from this energy via a numerical scaling factor calculated in CST Microwave Studios (©).

To extract the surface resistance of the sample plate the contributions to the measured intrinsic quality factor from the sample (Q_{sample}) and the host cavity (Q_{host}) must be decoupled. This is accomplished by separately measuring the quality factor with a different sample plate that is prepared identically to the host cavity. This will be referred to as the calibration measurement and assuming the calibration sample has identical surface resistance to the host cavity it can be used in conjunction with field integrals calculated in CST Microwave studios (©) to obtain the contribution to the quality factor from the host cavity. The calibration measurement (converted into average surface resistance) is shown in Fig. 2.

$$Q_{host} = Q_0^{calib}\left(\frac{\int_{host}|H|^2dA + \int_{plate}|H|^2dA}{\int_{host}|H|^2dA}\right) \quad (1)$$

Q_0^{calib} is defined as the intrinsic quality factor measured in the calibration measurement. Assuming this quality factor corresponding to loss on the host cavity will not change between the calibration measurement and the sample measurement and that extra sources of dissipation in the measurements are very small it can be used to find the contribution to the intrinsic quality factor from the sample:

$$Q_{sample} = \left(\frac{1}{Q_0^{sample}} - \frac{1}{Q_{host}}\right)^{-1} \quad (2)$$

Q_0^{sample} is defined as the intrinsic quality factor measured in the sample measurement. The surface resistance of the sample is:

$$R_{sample} = \frac{G}{Q_{sample}}\left(\frac{\int_{host}|H|^2dA + \int_{plate}|H|^2dA}{\int_{plate}|H|^2dA}\right) \quad (3)$$

G is the standard resonant cavity geometry factor.

ISSUES WITH THE CORNELL SAMPLE HOST CAVITY METHOD

This section highlights some important problems that have been encountered while using this sample test cavity. Problems that would impact any similar system are presented along with a discussion and attempted solutions to help guide the designs of researchers who wish to produce similar test systems.

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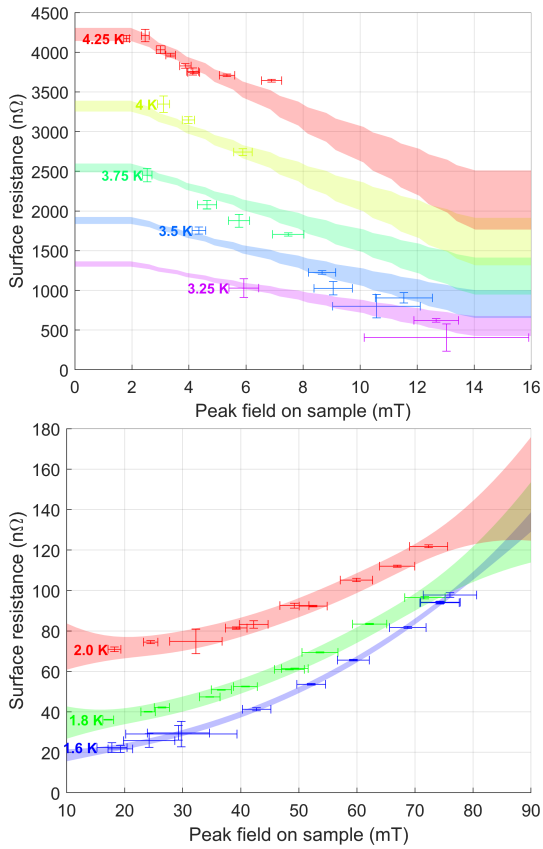

Figure 2: Measurement at 4 GHz of a low mean free path niobium sample plate with the preparation described in the apparatus section. A quench was observed in an unknown location for fields higher than ~ 80 mT. The fit (with shaded region showing uncertainty) for $T \leq 2.0$ K (bottom) is parabolic. For the higher temperatures (top) a measurement mistake prevented the collection of sufficient data for simple inference on all temperatures so a BCS fit was performed for various fields on 4.25 K, 3.75 K, 3.5 K, and 3.25 K and then extended to the less complete temperatures. The measurement will be repeated to obtain a cleaner calibration in the future.

Extra Dissipation

As was described in the measurements section, sample surface resistance is obtained by combining independent calibration and sample measurements to remove the contribution from the host cavity. A critical problem with this occurs if extra sources of dissipation are not identical and not small compared to the dissipation in the cavity in both measurements. These extra losses will manifest as an error in the reported sample resistance, ΔR. As can be derived similarly to Eq. (1) - Eq. (3) by including an extra quality factor corresponding to extra dissipation not seen in the cavity, the fractional error is given by:

$$\frac{\Delta R_{sample}}{R_{sample}} = -\left(\frac{\alpha \frac{Q_0^{sample}}{Q_0^{calib}} \frac{P_{extra}^{calib}}{P^{calib}} - \frac{P_{extra}^{sample}}{P^{sample}}}{\alpha \frac{Q_0^{sample}}{Q_0^{calib}} - 1} \right)$$

Where $\alpha = \frac{\int_{host} |H|^2 dA}{\int_{host} |H|^2 dA + \int_{plate} |H|^2 dA}$ and Q_0^i, P^i and P_{extra}^i denote the measured quality factor, the total power dissipated in the measurement, and power dissipated from any source other than the host cavity or plate respectively. The superscript describes whether the value comes from the calibration measurement or from the sample measurement. Figure 3 shows the potential impact of this error for different sample surface resistances. If the sample is less lossy than the low mean free path Nb calibration plate $\left(\frac{Q_0^{sample}}{Q_0^{calib}} \geq 1 \right)$ the error can be large and exceeds 100% for small amounts of extra dissipation. For a higher surface resistance sample $\left(\frac{Q_0^{sample}}{Q_0^{calib}} < 1 \right)$ the error is less severe than in the previous case but can become large when the extra dissipation is near the order of dissipation in the cavity.

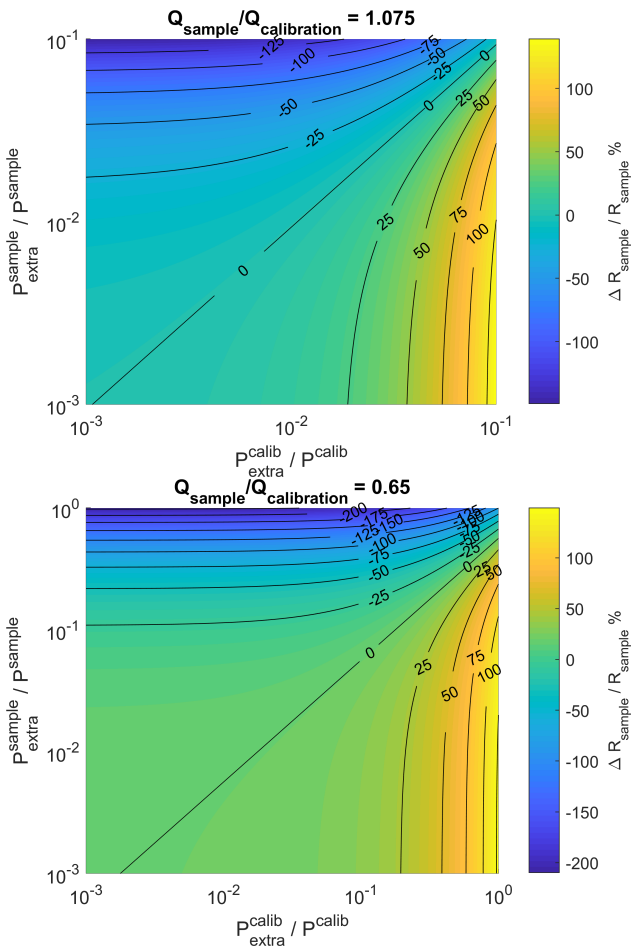

Figure 3: Percent error introduced in the extracted sample surface resistance in the presence of extra dissipation not on the host cavity or sample plate. The ratio of the extra dissipation to the total dissipation in the calibration and sample measurements is shown on the x and y axes. Two cases are given: (top) a sample that has lower surface resistance than the calibration plate and (bottom) a sample that has higher surface resistance than the calibration plate.

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In Cornell's sample host measurements it is apparent that a nontrivial source of extra dissipation considered above is likely occurring on the coupling antenna due to the dependence of the measured intrinsic quality factor on its position. If this dissipation is resulting from the TE_{011} mode fields then these losses are expected to increase as the coupler is positioned closer to the cavity. This is usually the case with some notable exceptions.

The problem has been difficult to solve for a number of reasons. The dissipation does not seem to be equivalent for the same position in different tests (perhaps due to the coupling and dissipation being sensitive to small changes in coupler angle) so it is not an option to leave it in a static location and expect the extra dissipation to cancel in the calibration. For measurement the coupler is positioned as far as possible from the cavity to minimize its dissipation but this is limited because moving the coupler away from the cavity increases the reflection. Specifically the limiting factors become the change in reflected power on and off of resonance becomes too small for the phase-locked loop to detect and the amount of power entering the cavity becoming too small for power meters to measure quality factor with acceptable signal-to-noise ratio.

Addressing this source of extra dissipation is critical to obtaining high resolution data for varying temperatures and field strengths on an arbitrary superconducting sample. For measurements of low surface resistance samples at low temperatures the coupler can be moved farther from the cavity so in this regime it is possible for the coupler to be in a position such that small changes do not noticeably impact the quality factor measurement. This becomes limited due to the small amount of power that can be coupled into the cavity in this position limiting the maximum field that can be obtained and usually making the power emitted from the cavity too low to reliably measure the characteristic decay time. For higher temperature measurements the coupler must be positioned farther into the cavity so more dissipation is expected and it is rarely in a position where its influence on the measured quality factor is negligible. Samples that have higher surface resistance than the niobium calibration sample are the most heavily impacted by this error as their measurement requires the maximum distance the coupler can be positioned from the cavity is less than that of the calibration sample. In this case minimizing the coupler position in both the sample and calibration measurements will result in a difference of extra dissipation moving the error away from the zero line in Fig. 3. The identification of the exact mechanism of this dissipation and its subsequent elimination is an essential step in improving the resolution of this sample measurement system.

Source of Coupler Loss

In an effort to reduce the impact of the coupling antenna in the quality factor measurement a new coupler design shown in Fig. 4 was developed to minimize coupler dissipation in the TE_{011} mode. Simulations of the new design in CST Microwave Studio (©) showed the dissipation on the new design was roughly 10% of the original over the relevant position ranges as is shown in Fig. 4. Little to no difference was observed when the new design was implemented. Using the conductivity of high RRR copper including the anomalous skin effect with simulation data reveals that the expected power loss from fields produced by the TE_{011} mode is far less than what is needed to produce the observed changes in measured quality factor. A possible explanation for this discrepancy is a low-Q mode near 4 GHz existing between the copper stem holding the coupling antenna and its stainless steel housing the leads up to the flange on which the cavity is placed. This explanation would be consistent with some (rare) observations of less dissipation for a coupler positioned closer to the cavity.

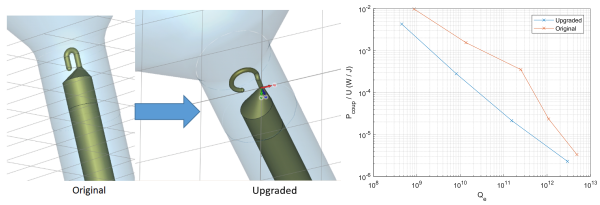

Figure 4: (Left) Original and new coupler designs. (Right) comparing original and new design power dissipation on the copper coupler from the field of the TE_{011} mode as a function of external quality factor corresponding to position of the coupler tip.

Ambient Magnetic Fields

DC magnetic fields present on the sample as it is transitions into the superconducting state can increase low temperature surface resistance measurements due to extra losses resulting from the interaction of RF fields with trapped magnetic flux vortices [7–9]. It is likely that the novel growth processes used for samples of interest have a higher probability of flux trapping defects than would be seen in typical SRF cavities and the little-studied materials investigated have unknown loss-sensitivity to these vortices. For the goal of measuring the intrinsic response of a sample it is therefore essential to minimize the ambient magnetic field present as it enters its superconducting phase. It is believed that until recently many low temperature measurements made with Cornell's system have been dominated by flux vortex dissipation [10]. Indeed, large magnetic fields have been observed by flux gate magnetometers placed on the sample disk though exact origins and characteristics are somewhat mysterious as they do not appear to strictly be generated by initial magnetization (small at room temperature) or thermal currents (persist when cryostat temperature gradients are small).

A possible explanation for the larger magnetic fields observed is the joint/clamps used to attach the sample plate to the host cavity. Interest in producing maximal strength RF fields on the flat sample plate requires joining the plate to the host cavity near a region of high fields/currents so any trapped flux in this region will have a strong effect on the

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measurement. In contrast standard SRF single-cell material tests have no flanges near the test region so if fields are generated by the flange it will not impact the measurement as heavily. The flange consists of metal-metal connections (niobium-indium-sample material) and clamps required to maintain vacuum against superfluid helium. Originally the Cornell system used large 316 stainless steel clamps for this joint but these were changed to titanium to remove potential sources of magnetization near the sample. Changing these clamps to titanium reduced ambient magnetic field at room temperature ($1 - 4$ mG) but produces larger thermal currents due to the titanium-niobium connection. Slowly cooling the cryostat to minimize thermal gradients seems to produce acceptably low trapped flux in measurements but more testing is needed for a full conclusion. The thermal current from the titanium clamp may be eliminated by replacing with G10 if it can provide sufficient clamping force or the titanium connections to other metals can be broken with Teflon spacers.

CONCLUSION

The sample host cavity at Cornell is capable of probing sample surface resistances with enough resolution to determine if they are viable candidates for further study towards SRF application. It can expose samples to an appreciable magnitude of continuous wave fields. Further improvements should be implemented to allow for careful comparison between produced data and theories. Careful data analysis shows that this limitation is not intrinsic to the measurement but is likely caused in part if not completely by extra dissipation somewhere in the system. This extra source depends on the coupler position but is too large to be caused strictly by dissipation from the TE_{011} fields. These clues may lead to identification of the source and its removal in the future.

For researchers considering implementing a similar design for sample testing they should carefully consider how the sample is attached to the host cavity to reduce RF losses on the joint and the production of magnetic fields on the sample as its proximity to support structures may lead to more issues than are seen in standard tests. The calibration measurement required to extract the surface resistance should allow for high resolution measurement but extreme care should be taken to eliminate any source of extra dissipation.

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