COMMISSIONING OF THE SRF SURFACE IMPEDANCE CHARACTERIZATION SYSTEM AT JEFFERSON LAB *

B. Xiao[1,2#], R. Geng[1], M. J. Kelley[1,2], F. Marhauser[1], H. L. Phillips[1], C. E. Reece[1], H. Wang[1]
[1]Jefferson Lab, Newport News, VA 23606, U.S.A.
[2]College of William and Mary, Williamsburg, VA 23187, U.S.A.

Abstract

Superconducting radio frequency (SRF) technology is widely adopted in particle accelerators. There remain many open questions, however, in developing a systematic understanding of the fundamental behavior of SRF materials, including niobium treated in different ways and various other bulk/thin film materials that are fabricated with different methods under assorted conditions. A facility that can measure the SRF properties of small samples in a range of 0~180 mT surface field and 2~20 K temperature is needed in order to fully answer these questions. The Jefferson Lab surface impedance characterization (SIC) system [1] has been designed to attempt to meet this requirement. It consists of a sapphire-loaded cylindrical Nb TE_{011} cavity at 7.5 GHz with a 50 mm diameter flat sample placed on a non-contacting end plate and uses a calorimetric technique [2-5] to measure the rf induced heat on the sample. Driving the resonance to a known field on this surface enables one to derive the surface resistance of the small localized area. TE_{011} mode identification has been done at room temperature and 4 K, and has been compared with Microwave Studio® simulation results. The variable input and transmitted rf couplers have been characterized. Rf loss mechanisms in the SIC system are under investigation. Thermal properties of the calorimeter have been well studied. A second generation calorimeter is being developed to optimize the dynamic range of the system. A prototype VCO phase lock loop system has been used in CW mode. Preliminary tests with bulk Nb samples have been done at <3 mT magnetic field. The presently available hardware is expected to enable up to 20 mT peak magnetic field on the sample, and paths to higher field tests have been identified.

DESCRIPTION OF APPARATUS

The SIC system is designed to measure the SRF properties of samples small enough to be accommodated in commercial surface characterization instruments, surface treatment facilities and laboratory-based thin film deposition equipment.

The basic concept of the SIC system is to put a sample that needs to be measured at the open end of a TE_{011} cylindrical niobium cavity with a sapphire rod inside, shown in Fig. 1. The rod lowers the resonant frequency of this size cavity to 7.5 GHz. This system provides controlled rf fields onto ~0.7 cm^2 on a 50 mm diameter sample.

The surface impedance of the sample can be derived by directly substituting heater heat for rf heat under controlled rf field and temperature conditions. See the next section for more detail. The sample temperature is feedback-controlled by the heater and thermo sensors. The sample is thermally isolated from the cavity body. Heat can be conducted from the sample only via the thermal insulator. This configuration is also convenient for future investigation of higher-T_c materials. The cavity interior and calorimeter are evacuated. The cavity is otherwise typically immersed in 2 K liquid helium during normal operation. Two rf choke joints are used at the bottom of the cavity to minimize the rf power leaking out of the cavity from the gap between the cavity and the sample.

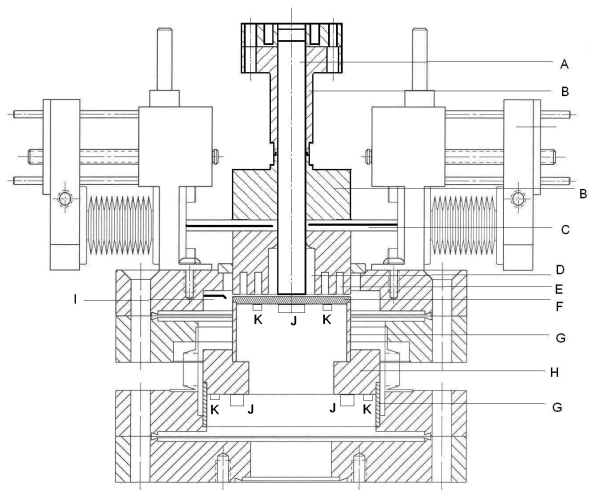

Figure 1: SIC system overview (Designed by J. Delayen, H. L. Phillips, H. Wang and B. Xiao) A. Sapphire rod, B. Nb, C. Coupler, D. TE_{011} cavity, E. Choke joint, F. Nb sample on copper plate, G. Stainless steel thermal insulator, H. Copper ring, I. Pickup coupler near the choke joint to monitor the rf leaking from the open gap, J. Heater, K. Thermal sensor.

EXPERIMENT

Parameters

The resonant frequency of the TE_{011} mode of the cavity can be tuned by adjusting the gap, the ratio of the frequency versus gap is the mechanical tuning sensitivity. Knowing this tuning sensitivity, one may derive the

* This manuscript has been authored in part by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
#bpx@jlab.org

change of surface reactance versus sample temperature from measurements of changes of the resonance frequency of the TE_{011} mode versus sample temperature. Simulation results of the tuning sensitivity are listed in Table 1. The tuning sensitivity has been measured at room temperature and 4 K, as -32 Hz/nm and -34 Hz/nm, respectively, shown in Fig. 2.

Table 1: Key Parameters to Derive Surface Impedance

Simulation	Tuning Sensitivity [Hz/nm]	$k\,[\frac{W}{\Omega T^2}]$	$\frac{H_{pk}}{\sqrt{U}}\left[\frac{T}{\sqrt{J}}\right]$
Closed gap MAFIA	-30		
Closed gap MathCAD		3.70×10^7	0.530
Closed gap MWS			0.503
0.2mm gap MWS	-30	3.62×10^7	0.336

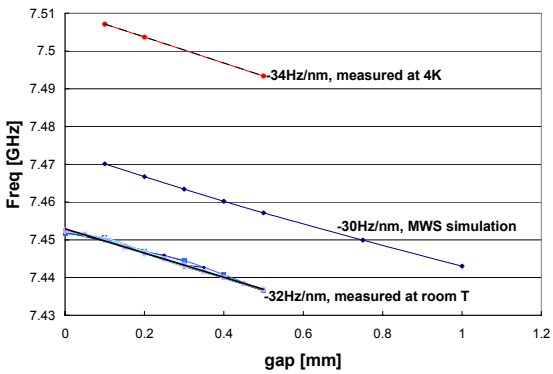

Figure 2: Tuning sensitivity of TE_{011} mode with 0.2 mm gap.

Surface resistance R_s can be derived in the following way. P_1 is the power from the heater required to keep a constant sample temperature without rf fields in the cavity; P_2 is the power from the heater required to keep the sample's equilibrium temperature unchanged when rf fields are present. Thus the rf induced heat: $P_{rf} = P_1 - P_2$. The following formula is used to derive surface resistance:

$$P_{rf} = \frac{1}{2}\int R_s H^2(S)dS$$

H(S) is the field distribution on the sample. $k = \frac{1}{2}\int H^2(S)dS \Big/ H_{pk}{}^2$ is geometry dependent, so

$$P_{rf} = kR_s H_{pk}{}^2$$

H_{pk} can be obtained from the stored energy since $H_{pk}/\sqrt{U}$ is also geometry dependent. Parameters k and $H_{pk}/\sqrt{U}$ are derived from the simulations. Results are given in Table 1.

Sample Preparation

The SIC system relies on a good thermal contact between sample and sample holder. The present SIC calorimeter system uses a Cu sample holder which thermally bonds well to a Cu substrate. In order to test a bulk Nb sample, a 0.2 mm thick Nb coupon was brazed onto a 2 mm thick Cu piece and then chemically or electrically treated. This Nb-on-Cu sample was mounted onto the Cu sample holder using Ga:In:Sn 1:1:1 in volume as the thermo-bonder.

Transition Temperature of bulk Nb

A vector network analyzer was used to measure the sample temperature dependence on the resonance frequency of the cavity, as well as its loaded Q. See Fig. 3. A transition temperature of 9.25±0.05 K has been measured. Since the transition temperature of Nb is 9.25 K, we conclude that the thermal impedance between the sample surface and the back of the sample holder (where temperature is measured, see Fig. 1) can be neglected compared with the thermal impedance between sample holder and liquid helium bath.

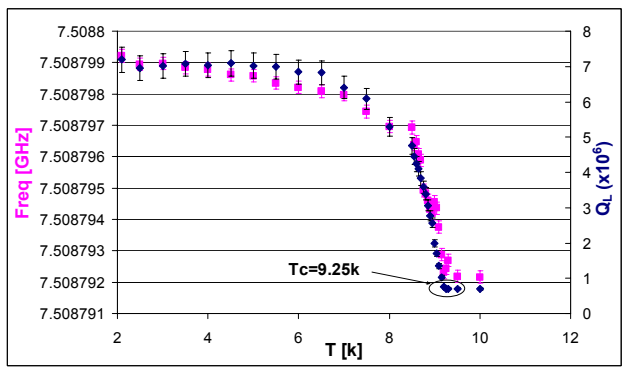

Figure 3: Frequency and loaded Q versus sample temperature for bulk Nb brazed on Cu substrate.

Surface resistance of bulk Nb

In an early use of the system, two tests have been done in the following sequence using a Nb/Cu clad sample as described above:

- Rapid cool to 4.5 K, then further cool to 2 K, measure the surface resistance.
- Return the same sample to room temperature, cool it to 100 K, hold for 1 hour, then continue cool to 4.5 K, then further cool to 2 K, measure the surface resistance.

Test results are shown in Fig. 4. Surface resistance measured here includes BCS resistance and residual resistance. A least-square multi-parameter fit [6] with Δ/kT_c and T_c fixed at 1.85 and 9.25 K, and the BCS resistance portion of this fit are shown in Fig. 4. One expects the surface resistance at 7.5 GHz of typical bulk niobium to be dominated by BCS to temperatures as low as 2K. The fit for this data suggests a residual resistance as high as 3.3 μΩ, higher than expected.

A comparison of the data from fast and slow cooldown tests demonstrate negligible parasitic losses due to

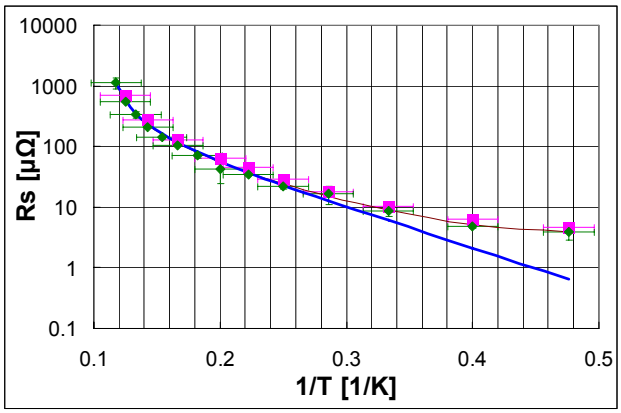

Figure 4: Surface resistance changes with sample temperature for bulk Nb brazed on Cu substrate. ■ Rapid cool, ◆ After staying at 100 K for 1 hour, — Least-square fit with Δ/kTc = 1.85, Tc = 9.25 K, London penetration depth = 43.8 nm, Coherence length = 22.4 nm, Mean free path = 99.3 nm and Residual Resistance = 3.27 μΩ, — BCS resistance.

hydride formation (Q disease) from excessive hydrogen adsorption during the preparation of the sample.

PATHS TO HIGHER FIELD

Currently the SIC system uses stainless steel as the thermal insulator in the calorimeter, (see Fig. 1). The high thermal impedance of stainless steel constrains the stable heat load and thus limits the magnitude of magnetic fields supportable in CW measurements. A second-generation calorimeter portion of the apparatus employing ETP copper as a thermal insulator is under fabrication. With this modification, the highest magnetic field in CW mode will be limited mainly by the available rf power. Figure 5 shows the measuring capability of the SIC system with a second-generation calorimeter. Solid lines show the anticipated conduction-limited operational bounds of copper-insulator design at equilibrium temperature with CW rf power.

With the current loaded-Q of 10^7 and 22 W available power from a TWT amplifier, the cavity can achieve peak magnetic fields up to 20 mT, shown in Fig. 5 with a dashed line. BCS resistance [7] and lower critical field [8,9] of Nb, Nb_3Sn and NbN at 2 K and 7.5 GHz are labelled in Fig. 5 to illustrate potential applications of the SIC system.

In order to approach 180 mT in CW mode, it will be necessary to improve the cavity's quality factor to 10^8 and use a 75 W rf source. For the current lower Q system, a pulse mode operation with a VCO control system is being developed.

SUMMARY

First tests that use the heat replacement technique at low field (<3 mT), enabling surface rf resistance measurements under different sample temperature conditions, have been completed. A second-generation calorimeter will be ready soon to achieve 20 mT fields in CW mode. It is anticipated that use of the SIC system will enable valuable and efficient correlation of local material characteristics with associated SRF properties, both for preparation studies of bulk niobium and also new thin film SRF developments.

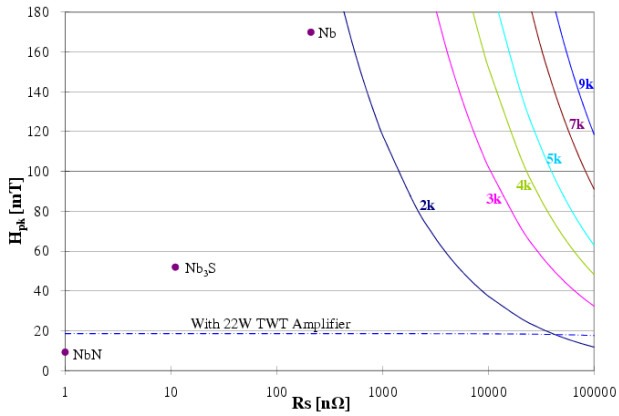

Figure 5: Measuring capability of SIC system with second-generation calorimeter.

REFERENCES

[1] L. Phillips, G.K.Davis, J. R. Delayen, J. P. Ozelis, T. Plawski, H. Wang, G. Wu, "*A Sapphire Loaded TE011 Cavity for Surface Impedance Measurements – Design, Construction, and Commissioning Status*", SRF2005, Ithaca, TuP46, (2005).

[2] D.L. Rubin, et al., "*Observation of a narrow superconducting transition at 6GHz in crystals of YBCO*", Phys. Rev. B, 38 (1988) 10.

[3] C. Liang, "*A New Surface Resistance Measurement Method with Ultrahigh Sensitivity*", p. 167 (1993).

[4] Mahner, E., et al., "*A new instrument to measure the surface resistance of superconducting samples at 400 MHz*", Rev. Sci. Instrum., p. 5, 74 (2003) 7.

[5] L.H. Allen, "*The Surface Resistance of Superconducting A15 Niobium-Tin Films at 8.6 GHz*", p. 98 (1986).

[6] G. Ciovati, "*SUPERFIT: a Computer Code to Fit Surface Resistance and Penetration Depth of a Superconductor*", http://tnweb.jlab.org/tn/2003/03-003.pdf

[7] G. Gemme, P. Fabbricatore, R. Musenich, R. Parodi, T. Rossi, M. Viviani, B. Zhang, "*RF Surface Resistance Measurements of Binary and Ternary Niobium Compounds*", J. Appl. Phys., p. 257, 77 (1994) 1.

[8] T. Tajima, "*Possibility of MgB_2 Application to Superconducting Cavities*", EPAC'02, Paris, June 2002, THPDO029, p. 2289 (2002).

[9] M. P. Mathur, D. W. Deis, J. R. Gavaler, "*Lower Critical Field Measurements in NbN Bulk and Thin Films*", J. Appl. Phys., p. 3158, 43 (1972) 7.