CRYOGENIC RF CHARACTERIZATION OF SUPERCONDUCTING MATERIALS AT SLAC WITH HEMISPHERICAL CAVITIES*

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Abstract

For the characterization of superconducting radio-frequency (SRF) materials, SLAC has commissioned a second-generation, X-band cavity cryostat for the rapid analysis of either thin-film coatings or bulk samples. With this test cryostat one can measure the sample's surface resistance, critical temperature, and magnetic quenching field. The system operates at a frequency of 11.4 GHz, at temperatures between room temperature and 4 K, and utilizes two interchangeable hemispherical cavities (one copper, one niobium) that can accommodate 2"-diameter (50.8 mm) samples on the flat surface. With the niobium cavity one can resolve surface resistances down to 0.7 $\mu\Omega$ (about one tenth of bulk niobium), while with the copper cavity one can measure quenching fields up to 360 mT (about twice that of bulk niobium).

INTRODUCTION

Bulk niobium SRF technology has reached a sufficient level of maturity such that it is being employed in a number of accelerators currently under construction [1]. Despite recent advances in niobium surface preparation, it still falls short of its theoretical potential. Thin films are an appealing alternative for a number a reasons (e.g. more materials options, reduced cost, better heat dissipation), but are yet to outperform bulk niobium in terms of both their quenching field or their RF surface loss. Extensive research efforts have been made in the area of SRF materials, both in bulk niobium and in thin-film coatings. The goal of these studies is to develop new materials with a) higher RF quenching field for higher accelerating gradient; b) higher T_c for higher operating temperature; and c) lower surface resistance for reduced dynamic loss. To support these efforts, SLAC has commissioned a new cryostat with two test cavities for the RF characterization of superconducting materials.

Researchers at SLAC have been developing this test bed over the past decade, beginning with the copper "mushroom"-shaped cavity [2-4]. About five years ago we switched to a hemispherical cavity design that provides for higher magnetic fields on the sample surface [5-6]. More recently we have added a niobium-coated cavity to our arsenal, with an intrinsic surface loss two orders of magnitude lower than our bare copper cavity. These two hemispherical cavities operate at 11.4 GHz and, along with a 50 MW SLAC XL-4 klystron, allow us to measure a sample's critical temperature, T_c, surface resistance, R_s, and magnetic quenching field, H_{quench}.

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CRYOSTAT & CAVITY DESIGN

The SLAC cryostat is built around a commercially-available pulse-tube cryorefrigerator from Cryomech (model no. PT415-RM). The remote-motor design of this model provides for reduced vibration levels and permits cavity measurements while actively cooling. Implemented in our system, the second stage of the cryorefrigerator has a base temperature of 3.6 K, with about 0.7 W of dynamic cooling power at 4.2 K. The entire cryostat can be cooled from room temperature to base in less than four hours. A complete measurement cycle in one of our cavities (including sample loading, pump-down, cool-down, and warm-up) can take less than 24 hours.

The key components of our measurement system are the hemispherical cavities (see Fig. 1). Both are machined in two parts (sample plate and dome) from high-purity copper. The niobium cavity has a thin-film coating applied to these parts (deposited by Sergio Calatroni's group at CERN) and a smaller-diameter choke to achieve critical coupling at 4 K. X-band operation permits a small sample size and compact cavity design – the sample diameter is 2.0 in. (50.8 mm) and the cavity base plate has an outer diameter of 5.6 in. (142 mm). Utilizing a variety of mounting plates, our cavities can accommodate sample thicknesses from 0.017"–0.250" (430 μm – 6.35 mm). By

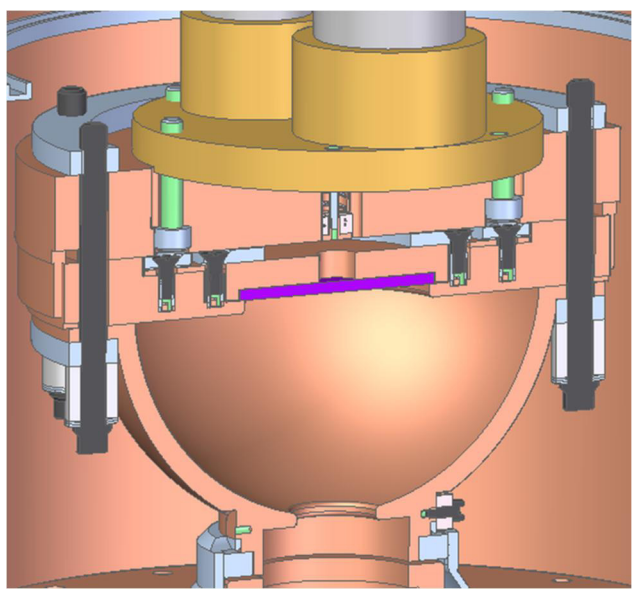

Figure 1: Rendering of SLAC's hemispherical test cavity. The cavity is mounted to the second stage of a pulse-tube cryorefrigerator, with RF power fed from the bottom. The sample under test (purple) is mounted on the flat surface of the cavity. SLAC has two such test cavities: one bare copper, and a new niobium-coated one.

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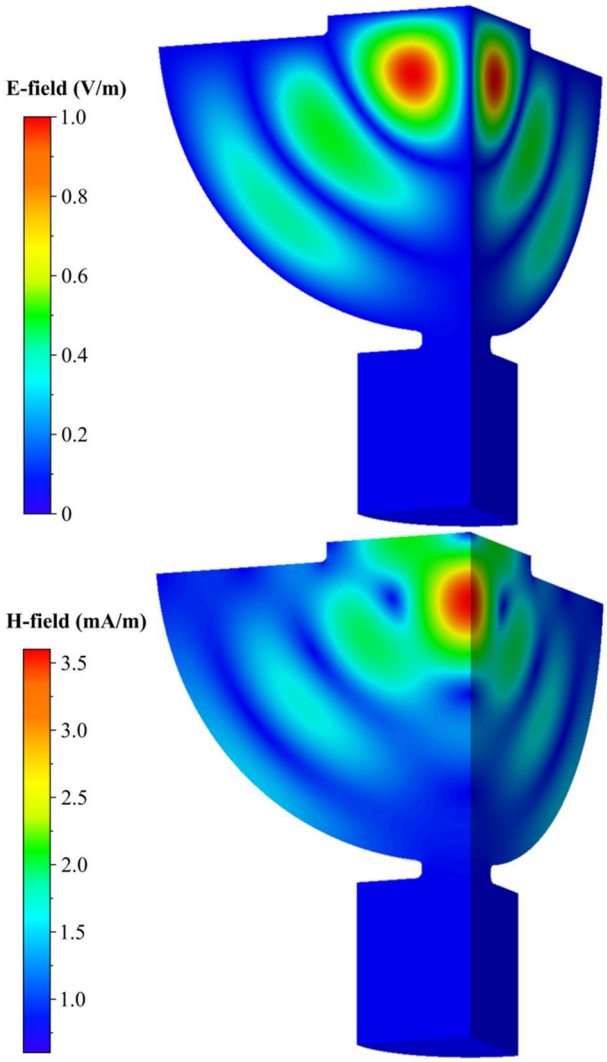

Figure 2: HFSS modelling of our hemispherical cavity. At 11.4 GHz the cavity has a TE_{032}-like mode where the magnetic field is focused on the sample, and the electric field there is zero.

measuring the unloaded quality factor, Q_0, of the niobium cavity, R_s of the sample can be characterized as a function of temperature. Surface magnetic fields can be calculated from the input power and quality factors, so H_{quench} can be found by measuring Q_0 at different power levels in our copper cavity.

Both cavities are designed to operate at 11.4 GHz with a TE_{032}-like mode where the magnetic field is strongest on the sample surface, limiting the contribution of the cavity material to the overall cavity loss. Using the HFSS EM simulator (see Fig. 2) we find that the magnetic field is 2.5 times higher on the sample than anywhere on the cavity dome, and that the electric field on the sample is zero. In addition, the magnetic field on the sample surface is entirely radial, which gives rise to azimuthal surface currents. Simulations also show that, despite comprising less than 8% of the total surface area, the sample accounts for 33% of the total cavity loss.

Table 1: Simulated Design Values for Both Cavities

Parameter	Cu Cavity	Nb Cavity
Q_{total}	1.7e5	1.6e7
G_{total}	1393 Ω	1403 Ω
α_{body}	0.674	0.670
α_{sample}	0.326	0.330

Taking the simulation results, one can integrate over the surface fields to relate Q_0 to the total surface resistance, R_{total}, through a total geometrical factor, G_{total}:

$$\frac{1}{Q_0} = \frac{R_{total}}{G_{total}}.$$

R_{total} is simply a linear combination of the cavity body surface resistance and the sample surface resistance, so the cavity loss can be written as

$$\frac{1}{Q_0} = \frac{\alpha_{body} R_{body} + \alpha_{sample} R_{sample}}{G_{total}},$$

where the α's are the participation ratios for the cavity body and sample, with unity sum. The participation ratios are determined by relating the geometrical factors for the cavity body and sample to G_{total}:

$$\alpha_{body} = \frac{G_{total}}{G_{body}},$$

$$\alpha_{sample} = \frac{G_{total}}{G_{sample}}.$$

The geometrical factors and participation ratios (along with other design parameters) for both cavities are shown in Table 1.

CAVITY MEASUREMENTS

Sample measurements in our copper cavity have been published previously, so we will only summarize those here. Because copper does not quench or have a transition temperature like superconductors do, it is an ideal cavity for measuring H_{quench} and T_c. Using an XL-4 klystron as the RF source, with 1–2 μs pulses, one can reach sample surface fields of up to 360 mT, nearly twice that of bulk niobium. The short pulses have the added benefit of not dumping too much heat into the cavity, and changing the temperature of the sample during measurement. For measuring T_c we instead connect the cavity to a vector network analyser and do a low-power temperature sweep.

The limitation of the copper cavity is that it does not allow for high-resolution measurement of the sample R_s – at 4 K and 11.4 GHz, copper is nearly 100 times more resistive than niobium, so any measure of Q_0 is dominated by the cavity body. This is not the case in our new niobium-coated cavity. Measuring our niobium reference

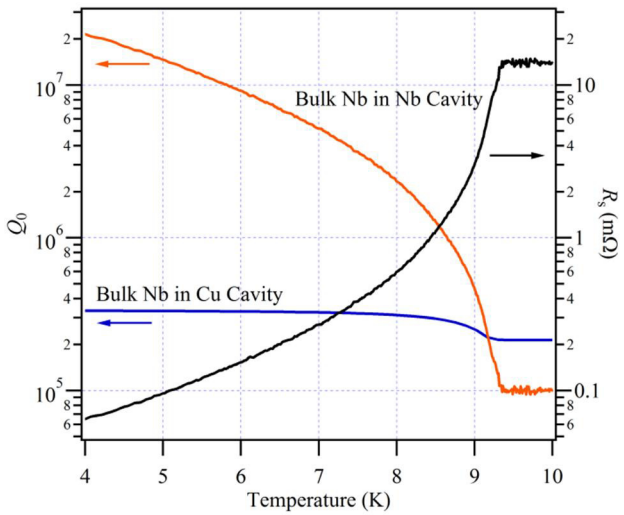

Figure 3: Single-crystal bulk niobium reference sample measured in both the copper and niobium cavities. The orange and blue curves illustrate the difference in Q_0-sensitivity. From the measurement in our niobium cavity we can calculate R_s using G_{total}.

sample (single-crystal bulk niobium) in both cavities illustrates this difference (see Fig. 3). Whereas in the copper cavity Q_0 plateaus rapidly below T_c, in the niobium cavity Q_0 continues to increase all the way down to 4 K.

To determine the sample R_s in either cavity, one needs an appropriate reference sample, made from the same material as the cavity body. We have such a sample for our copper cavity, but unfortunately we do not for the niobium one. If we assume that the single-crystal bulk sample has an R_s identical to that of the niobium coating in our cavity, the value derived from Q_0 and G_{total} at 4 K and 11.4 GHz is 65 $\mu\Omega \pm 1\%$. Furthermore, assuming a temperature dependence of $(T/T_c)^4$ (the two-fluid model result) and a frequency dependence of ω^2, this translates to 47 nΩ at 2 K and 1.3 GHz. See Fig. 3 for a plot of R_s vs. temperature.

We have noted above an uncertainty of 1% in the calculated R_s value. This figure is nothing more than the standard deviation of the raw data from a fitting function. (For our purposes, we use a simple quadratic function for $\log(R_s)$ or $\log(Q_0)$ over the temperature range 4–6 K.) We have also evaluated the run-to-run consistency of our cryostat and niobium cavity by repeatedly measuring our bulk niobium reference sample. These repeats include thermal cycling and disassembly of the cryostat and cavity, and over four separate runs spanning about six weeks, the measured Q_0 at 4 K varied by about 1%. We will continue to monitor our system over time, but these levels of resolution and precision gives us confidence in our ability to characterize SRF materials.

To put our cavity cryostat to the test, we have already measured a number of thin film samples provided to us by various partners. Included among these are Nb films on stainless steel from Alameda Applied Sciences Corp., and Nb films on Cu from JLab. We have also tested MgB_2 films on both sapphire and copper substrates from Temple University. Q_0 measurements from a few of these samples are shown in Fig. 4. This data is fed back to our partners and is a key metric for film growth optimization.

CONCLUSION

SLAC has recently commissioned a second-generation, X-band cavity cryostat for the rapid analysis of SRF thin-film coatings and bulk samples. Through the use of both a copper cavity and a niobium-coated one, we can measure all of the RF properties of interest: R_s, H_{quench}, T_c. With the niobium cavity we can resolve R_s down to 0.7 $\mu\Omega$ at 4 K

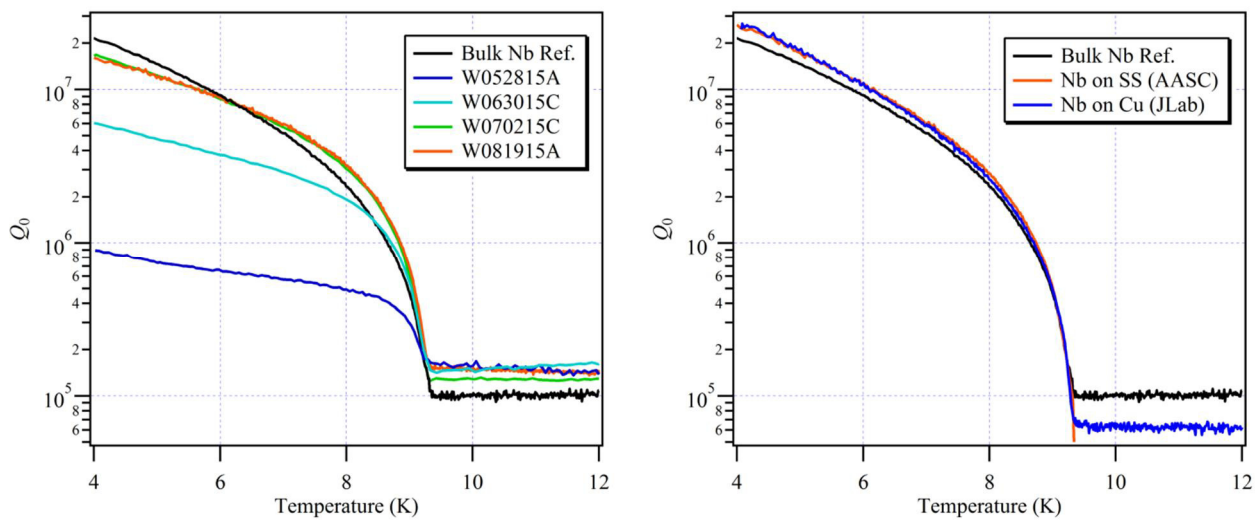

Figure 4: SRF materials characterized in our niobium cavity. Left: MgB_2 films on copper from Temple University. RF characterization at SLAC has already led to some process improvement. (Note that T_c here is that of our cavity – in the copper cavity, T_c of the best films is 38 K.) Right: Nb films on stainless steel from Alameda Applied Sciences Corp., and on copper from JLab. Both show promise when compared with our bulk niobium reference sample.

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and 11.4 GHz, while with the copper cavity we can measure H_{quench} up to 360 mT. Our Q_0 measurements in niobium have both high resolution and are consistent from run to run. We have utilized this system to analyze thin film coatings from a number of partner laboratories, providing feedback to those researchers to optimize deposition parameters. Our system is an ideal test bed for SRF materials characterization and development.

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REFERENCES

[1] D. Gonnella et al., "Nitrogen-doped 9-cell cavity performance in a test cryomodule for LCLS-II," J. Appl. Phys. **117**, 023908 (2015).

[2] C. Nantista et al., "Test bed for superconducting materials," Proc. Part. Accel. Conf. PAC05, 4227 (2005).

[3] S. Tantawi et al., "Superconducting materials testing with a high-Q copper RF cavity," Proc. Part. Accel. Conf. PAC07, 2370 (2007).

[4] A. Canabal et al., "Critical magnetic field determination of superconducting materials," Proc. Euro. Part. Accel. Conf. EPAC08, 919 (2008).

[5] J. Guo et al., "A cryogenic RF material testing facility at SLAC," Proc. Intl. Part. Accel. Conf. IPAC10, 3049 (2010).

[6] J. Guo et al., "Cryogenic RF material testing at SLAC," Proc. Part. Accel. Conf. PAC11, 1030 (2011).