CRYOGENIC RF MATERIAL TESTING AT SLAC*

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Abstract

We have been developing an X-band cryogenic RF material testing system since 2005. By measuring the Q of a hemispherical cavity with the material sample at is flat interchangeable bottom, the system is capable to characterize the surface resistance of different materials at the temperature of 3-300K, as well as the quenching RF magnetic field of the superconducting samples at different temperatures. Using a SLAC X-band 50MW klystron, the system can measure the quenching H-field of up to 300mT under current setup, with the possibility of further enhancement by changing the RF distribution configuration.

INTRODUCTION

The success of the Niobium superconducting RF technology makes it more and more attractive. Extensive research efforts are being made in the superconducting materials study, in hope to find new materials with higher quenching RF magnetic field for higher accelerating gradient, at the same time with higher T_c and/or lower surface resistance to reduce the cryogenic load. Such new materials may enable a lot of new particle accelerator applications. Several existing bulk BCS superconductors like MgB_2, NbN or Nb_3Sn have larger energy gap and transition temperature compared to Nb, resulted in lower surface resistance and higher *thermodynamic critical field* H_c, but the *lower critical field* H_{c1} is much lower than Nb due to the shorter coherence length. A possibility to enhance H_{c1} was suggested by using multi-layers of superconductor films thinner than the London penetration depth with insulator in between [1]. A lot of material samples have been developed [2] to demonstrate this theory.

To facilitate the SRF material research, we developed an SRF testing system capable to measure the quenching field and surface resistance of a flat sample disk with 2-3 inches diameter. The system operates at 11.4GHz, using a 50MW klystron with 1-2μs pulses. The earliest system uses a "mushroom" shape copper cavity with a flat bottom to host the samples [3, 4, 5]. Then the cavity shape was changed to hemispheric [6], which can provide higher H in the bottom. The instrumentation of the system is also improved. Currently, a niobium cavity with similar shape is under development, which will be dedicated for low power surface resistance characterization.

SYSTEM DESIGN

The key component of the system is the hemispheric cavity, with the detail shown in Fig 1. By measuring the unloaded quality factor Q_0 of the cavity, surface resistance of the sample will be characterized. Surface field can be calculated from the input power and quality factors, so the quenching filed can be found by measuring Q_0 at different power level. The cavity operates at approximately 11.4GHz under a TE_{013} like mode.

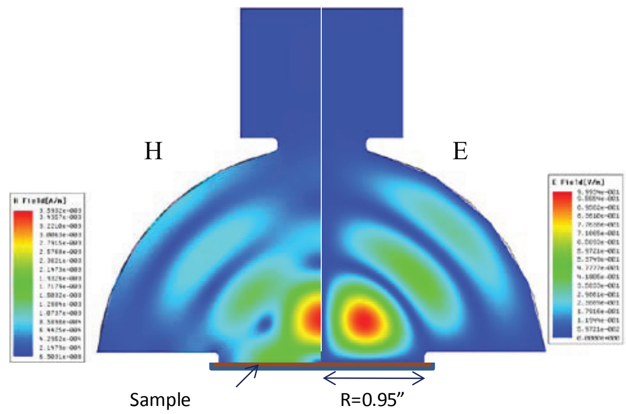

Figure 1: Fields in the hemispheric cavity.

For the cavity with a sample plate, the quality factor can be written as

$$Q_0 = \frac{1}{\dfrac{R_{s,body}}{G_{body}} + \dfrac{R_{s,sample}}{G_{sample}}}.$$

$R_{s,\ sample}$ is the surface resistivity of the sample, and $R_{s,body}$ is the surface resistivity of the other part of the cavity. G_{sample} is the geometry factors related to the sample part and G_{body} comes from the rest of the cavity. $R_{s,body}$ can be obtained by measuring the quality factor with a reference sample same as the body material

$$R_{s,body} = \frac{1}{\left(\dfrac{1}{G_{body}} + \dfrac{1}{G_{sample}}\right) Q_{0,ref}}$$

The sample surface resistivity can be calculated using the measured cavity quality factor with the sample:

$$R_{s,sample} = G_{sample}\left(\frac{1}{Q_0} - \frac{R_{s,body}}{G_{body}}\right)$$

To characterize the RF magnetic quenching field, it's essential to maximize the H-field on the sample while eliminating all other factors that may cause a change in Q. Those factors may include sample RF breakdown or multipacting caused electric field, thermal quench caused

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by pulse heating, or the quench of the cavity body. TE_{013} mode in a hemispheric cavity is an ideal choice because its bottom surface has a high magnetic field but no electric field. The peak magnetic field on the sample surface is approximately 2.5 times of the peak on the dome. This also concentrates the RF losses on the sample, giving a lower ratio between G_{sample} and G_{body}, which will result in more precise R_s characterization. For the hemispheric cavity at 11.4GHz, we have $G_{body} = 2166$ and $G_{sample} = 3902$ from HFSS simulation.

The resonant frequency of the cavity was chosen at 11.4GHz. At this frequency, the size of the system and the samples can be small enough and easy to build. This also allows us to use the SLAC RF sources and other facilities. To build up a given H-field, the stored energy is much less than cavities at lower frequency. Although BCS surface resistance is proportional to the square of frequency, which is causing higher pulse heating, the reduction in stored energy and thus the shorter pulse length can mitigate this problem. With higher available peak power from the klystron, the pulse length is further reduced, and the pulse heating might be less serious than the systems of lower frequency.

Copper is chosen as the material for the cavity, because it has a low surface resistance which is independent of RF field level. Electric breakdown is not likely to happen at the field level in this cavity. The surface resistance of copper doesn't have a superconductor like temperature dependence, making it possible to characterize the samples at higher temperature. With a reference sample, the cavity has a Q_0 of about 50,000 at room temperature and 224,000 at 4K. Q_{ext} is approximately 350,000, making the cavity critically coupled when the sample is close to zero resistivity.

Since the H-field in the cavity is concentrated near the sample, the cavity parameters are very sensitive to geometric perturbations at the bottom. Simulation shows that when the step height between the sample and the larger bottom plate changes by 0.01 inch (0.254mm), Q_{ext} will change by approximated 1/3; G_{sample} will change by about 4% while G_{body} changes approximately 1% in the other direction; frequency will change by about 40MHz. The geometric change is very hard to avoid if different type of samples with different dimension need to be tested. In this case, precision of the surface resistance measurement will be very limited with a copper cavity. Recently a new bottom plate have been designed and built, reducing the deformation of the cavity with different samples.

A niobium cavity is also under fabrication, which can improve the low power characterization of surface resistance. The Nb cavity has similar shape as the copper version with an enlarged iris, increasing Q_{ext} to about 1×10^7 to fit with higher Q_0. Q_{ext} can be also adjusted by the step height between the sample and the bottom plate.

EXPERIMENT RESULTS

Numerous samples have been tested in our system in the past years, including different copper, molybdenum, niobium and MgB2 samples. We are focusing on the Nb sample test results in this paper. The most recent results of the MgB_2 thinfilm samples will be reported in [2]. In the high power tests reported in this paper, the input pulse width is chosen at 1.6μs.

FNAL Small Grain Niobium

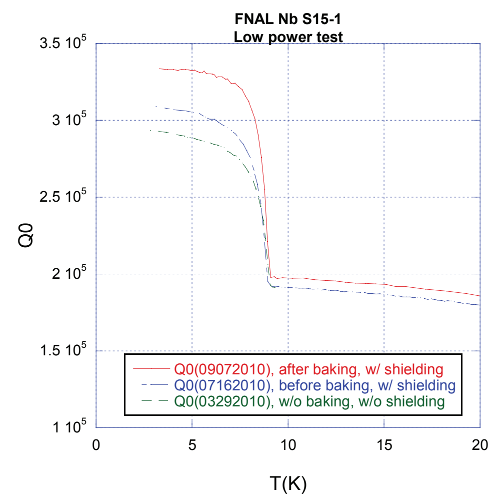

Figure 2: Low power test, FNAL small grain Nb.

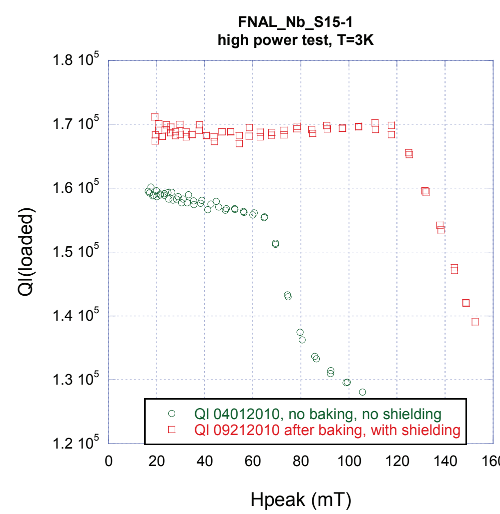

Figure 3: High power test, FNAL small grain Nb.

We have tested a small grain Niobium sample provided by Lance Cooley of Fermilab. The sample was first tested as received. The Q_0 for the low power test is shown as the green curve in Fig.2, and the green in Fig.3 is the high power test Q_l (loaded Q). The residual resistance is approximately 2mΩ, which is extremely high and causes thermal quenching at 65mT in the high power test.

Similar results were observed in other samples. Then we added magnetic shielding in the system, some improvement is shown in the blue line in Fig. 2, but still has significant residual resistance. After that, the sample is cleaned with H_2SO_4:H_2O_2, HF:H_2O, HCl:H_2O_2 solutions sequentially, and then vacuum baked at 800°C for 8 hours. The baked sample is tested with magnetic shielding. The test results are shown in the red curves in Fig. 2 and Fig. 3. The residual resistance at the temperature of 4K is reduced to the level lower than what can be measured by the system, the resistance at normal conducting state also reduced slightly. The quenching field increased significantly to 120mT.

LANL Single Grain CMP Niobium

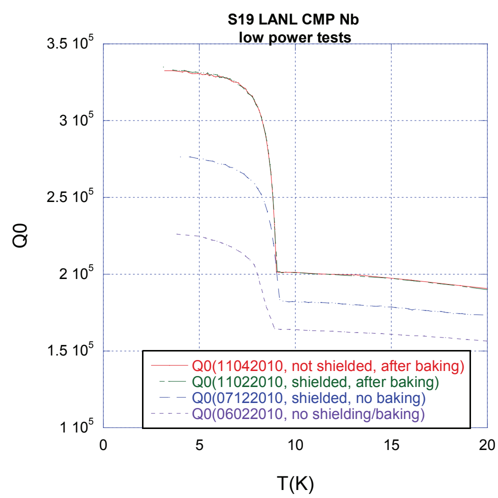

Figure 4: Low power test, LANL CMP Nb.

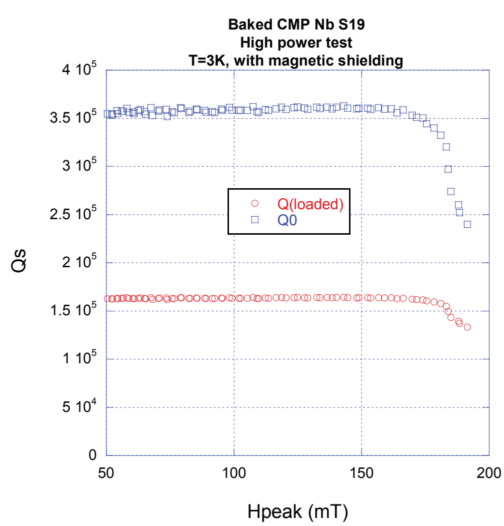

Figure 5: High power test, LANL CMP Nb.

A single grain CMP (chemical mechanical polish) niobium sample was tested. The sample is provided by Tsuyoshi Tajima of LANL, and similar substrates will be used for the development of the MgB_2-insulator-Nb multilayer system in [2]. The sample was tested with low power with different treatment and setup, with results shown in Fig. 4. Before cleaning/baking, the residual resistance was about 6mΩ without magnetic shielding, about same as the resistance of copper, the normal conducting state resistivity was also very high; with magnetic shielding, the residual resistance reduced by about half. After the same cleaning/baking process as the FNAL small grain sample, this CMP Nb sample was tested again. For both tests with and without magnetic shielding, the residual resistance are also lower than the limit of what the system can measure. The sample was high power tested only once, after the cleaning/baking and with magnetic shielding. The quenching field reached about 170mT, as shown in Fig. 5.

SUMMARY

We have demonstrated a cryogenic RF material testing facility capable to precisely measure the quenching RF magnetic field for superconducting sample disks with 2-3 inches diameter. The maximum magnetic field in the current system can be up to 300mT. The system can also be used to characterize the surface resistance of both superconducting and normal conducting samples. The precision of surface resistance measurement is being improved.

Several niobium samples have been tested. Most of the samples have high residual resistance when received and are prone to have thermal quench caused by pulsed heating, but cleaning and baking can effectively reduce the residual resistance and enhance the quenching magnetic field. Magnetic shielding also helps to reduce the surface resistance by approximately half, but not effective enough in our system.

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