TESTING THE RF PROPERTIES OF NOVEL SUPERCONDUCTING MATERIALS *

Jiquan Guo#, Sami Tantawi, David Martin, Charles Yoneda

SLAC National Accelerator Laboratory, Menlo Park, CA, U.S.A.

Abstract

An X-band RF cryogenic material testing system has been developed at SLAC in the past few years. The system is capable to measure the RF surface resistance of superconducting and normal-conducting materials at the temperature of 3K to 300K, and to characterize the RF quenching magnetic field of superconducting materials. This system employs a high-Q hemispheric cavity with an interchangeable flat bottom hosting a 2-3 inch diameter sample disk. Using a klystron with 50MW 2μs output pulse, the system can measure the quenching H field of about 300mT, and is possible to achieve 700mT by changing the RF distribution configuration.

INTRODUCTION

Niobium superconducting RF technology provides much lower surface resistance and losses, and is becoming more and more attractive for accelerator applications. For many accelerator systems, especially in the accelerators with an RF system under constant wave or high duty cycle operation, the total wall plug power required to achieve the same gradient in a niobium cavity can be significantly less than normal conducting cavities.

To make niobium SRF cavities suitable for high energy accelerators, lot of research progress has been made over the past decades, increasing the accelerating gradient by overcoming the problems caused by high electric and magnetic fields, raising the maximum acceleration gradient from 3MV/m to about 50MV/m, reaching a theoretical limit set by the *lower critical field* H_{c1} of 170-180mT or the *thermodynamic critical field* H_c of about 200mT.

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. Such new materials may enable a lot of new particle accelerator applications. Several BCS superconductors like MgB_2 and Nb_3Sn have larger energy gap and transition temperature compared to Nb, resulted in lower surface resistance and higher H_c, but 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] trying to demonstrate this theory.

To facilitate the SRF material research, we started to develop an SRF testing system in 2005, which is capable to characterize the quenching field and surface resistance of a flat sample disk with 2-3 inches diameter by measuring the quality factor of a RF cavity. The system operates at 11.4GHz, making it compact in size and needs less energy to build up the RF field in the cavity. Although the system uses a 2μs 50MW SLAC klystron, the current setup only feeds the maximum power of about 2-3MW into the cavity in order to minimize the power reflected back into the klystron and make it easier to produce a flat input pulse. This setup can achieve a maximum H-field of almost 300mT on the sample, and can be enhanced further to 700mT or more by changing the RF distribution.

Our earliest system uses a "mushroom" shape copper cavity with a detachable flat plate to host the samples [3, 4, 5]. The cavity operates under a TE_{013} like mode, which has no radial E-field and current on the wall, and allows a simple demountable sample plate with a small gap. The H-field is concentrated in the sample area. In the recent years, the cavity shape was changed to hemispheric, which can provide higher H in the bottom. However, a more optimized mushroom cavity is under consideration. The copper cavity has many advantages for high power testing, but will have lower accuracy in low power surface resistance characterization, estimated at 0.1-0.2mΩ. A thinfilm niobium cavity with similar shape is under development with the collaboration of CERN.

EXPERIMENT DESIGN

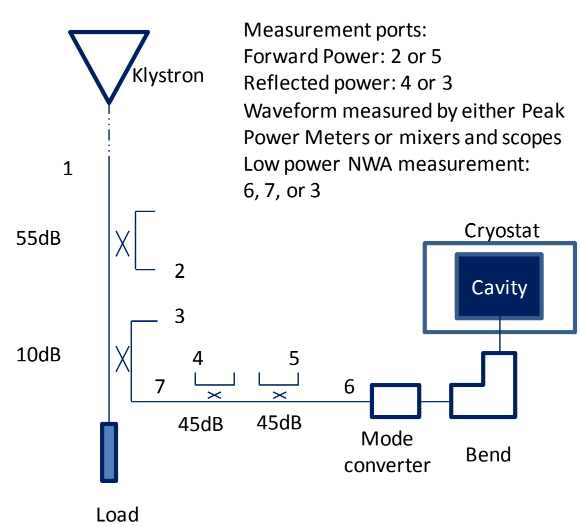

Figure 1: System diagram

*Work supported by the U.S. Department of Energy
#jqguo@slac.stanford.edu

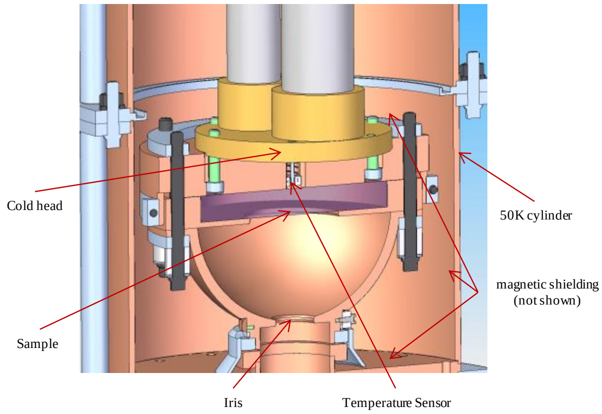

Figure 2: The assembly of the hemispheric cavity

Our testing system comprises an RF cavity in a cryostat, and an RF network with the instrumentation that can measure the quality factors of this cavity under high power and low power separately, as shown in Fig. 1.

The key component of the system is the hemispheric cavity with a detachable flat plate hosting the sample, as shown in Fig. 2. The cavity sits in a cryostat, which is cooled by a closed loop helium refrigerator. Magnetic field is shielded with a cylinder of CO-NETIC AA alloy sheets. From the results discussed later in this paper, we can see that the shielding can significantly reduce the residual resistance. However, the cylinder has to leave two holes for the coldhead and the input waveguide, which may still lead to some field leak.

Cavity Characterization

By measuring the unloaded quality factor Q_0 of the cavity, surface resistance of the sample can be characterized. For low power characterization, reflection coefficient of the cavity is measured with the network analyzer from point 3, 6 or 7 in Fig. 1. The loaded and unloaded quality factors are determined by Q circle fitting of the measured data.

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

$$Q_0 = \frac{1}{\frac{R_{s,body}}{G_{body}} + \frac{R_{s,sample}}{G_{sample}}} \quad (1)$$

$R_{s,\,sample}$ is the surface resistivity of the sample, and $R_{s,body}$ is the surface resistivity of the rest of the cavity. G_{sample} is the geometry factors related to the sample part and G_{body} comes from the rest of the cavity, which can be found from electric-magnetic field solver programs. $R_{s,body}$ can be obtained by measuring the quality factor of the cavity with a reference sample made of the same material as the body.

$$R_{s,body} = \frac{1}{(\frac{1}{G_{body}} + \frac{1}{G_{sample}})Q_{0,ref}} \quad (2)$$

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

$$R_{s,sample} = G_{sample}(\frac{1}{Q_0} - \frac{R_{s,body}}{G_{body}}) \quad (3)$$

High Power Characterization

The high power characterization will measure the quality factors at different RF field levels, and determine the quenching field. The cavity will be charged with a square RF pulse at the resonant frequency from the klystron, as shown in Fig. 1. The 10dB directional coupler is used to reduce the power reflected between the cavity and the klystron, making it easier to get a flat pulse.

Before the pulse ends ($0<t<T_p$), the energy stored in the cavity U_c follows

$$U_c = P_F t \frac{2\beta}{1+\beta} \frac{\left(1-e^{-t/T_f}\right)^2}{t/T_f} \quad (4)$$

where P_F is the forward RF power, t is the time from the start of the pulse, $\beta = Q_0/Q_e$ is the coupling coefficient, and $T_f = 2Q_l/\omega$ is the cavity filltime. The peak H-field is proportional to the square root of the stored energy.

$$H_{peak} = g\sqrt{U_c} \quad (5)$$

Peak H-field coefficient g is another geometric factor which can be found from electric-magnetic field simulation. To maximize the cavity charging efficiency $\eta = U_c/(P_F T_p)$, the pulse width T_p needs to be close to 1.26 times of the cavity filltime and the coupling coefficient needs to be large. Larger β is also helpful to increase the efficiency, but will lower the accuracy of Q_0. The highest possible charging efficiency is 81.4% with an extremely large β; at critical coupling, the maximum efficiency is 40.7%.

The output power from the cavity will be

$$\frac{P_{out}}{P_F} = \begin{cases} \left(\frac{2\beta\left(1-e^{-t/T_f}\right)}{1+\beta} - 1\right)^2, 0<t<T_p \\ \left(\frac{2\beta\left(1-e^{-T_p/T_f}\right)}{1+\beta}\right)^2 e^{-2(t-T_p)/T_f}, T_p < t \end{cases} \quad (6)$$

In the experiment, the trace of both the forward and the output RF power will be recorded. The filltime and Q_l can be calculated by fitting the decay of the output power after the input pulse. Q_0 and β can be either calculated from the low power measured Q_e, or by fitting the power trace during and after the input pulse. The stored energy and H_{peak} can be then calculated from eq. (4) and eq. (5), using the measured average forward power.

Cavity Design

To characterize the RF magnetic quenching field of the sample, it's also essential to eliminate all other factors that may cause a change in Q. Those factors may include RF breakdown or multipacting caused by electric field, thermal quench caused by pulse heating, or the quench of the cavity body. TE_{0nm} mode in an axially symmetric cavity is an ideal choice because it has no electric field on all the surfaces, and has a high magnetic field on the bottom surface. Another advantage of this type of modes is that the surfaces have only azimuthal current, which can minimize the RF leak from the small azimuthal gaps. This reduces the requirement of electric contact between the sample, the sample holder plate and the cavity body, resulting a simple detachable sample holder design and easy installation process.

To be able to achieve high H_{peak} on the sample surface for a given input, it is also preferred to maximize the geometric factor g. Concentrating H_{peak} on the sample surface also gives a lower ratio between G_{sample} and G_{body}, which will increase the accuracy of R_s characterization.

A circular TE_{011} pillbox may be the simplest and most compact choice, and it will be able to maximize g when the aspect ratio is optimized. However, such a cavity has high magnetic field on both endplates. This not only increases the ratio between G_{sample} and G_{body}, but also makes it hard to design the coupling for the cavity. The coupling hole needs to be on the side of the pillbox, which breaks the axial symmetry and will excite unwanted modes, resulting in unacceptably low measurement accuracy.

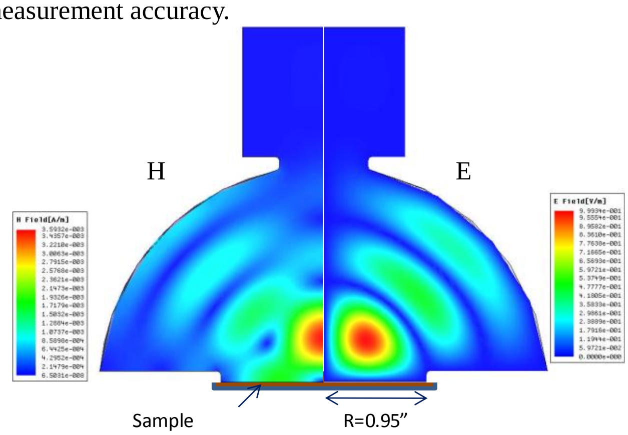

Figure 3: Fields in the hemispheric cavity

Currently, we choose a TE_{013} like mode in a hemispheric shape cavity as shown in Fig. 3. For this mode, H_{peak} only occurs on the sample surface, and allows an axial symmetric coupling aperture at the top of the cavity. The other side of the aperture is a circular waveguide operating under TE_{01} mode. The coupling coefficient is very sensitive to the thickness and diameter of the aperture, making it easily adjustable to different version of cavities.

In the current hemispheric cavity, the peak magnetic field on the sample surface is approximately 2.5 times of the peak on the dome. For the hemispheric cavity at 11.4GHz, we have G_{body}=2166Ω and G_{sample}=3902Ω from HFSS simulation. Although the sample area is only about 8% of the total area of the cavity inner surface, it will account for about 36% of the losses if the cavity body and the sample are made of the same material. The peak H-field coefficient g=271mT·J$^{-1/2}$ is about 2/3 of the optimized circular TE_{011} pillbox.

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 and shorter fill time of the copper cavity, 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 copper. 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 340,000, making the cavity critically coupled when the sample is close to zero resistivity. In that case, the fill time will be about 4.8μs. With a 1.6μs input pulse, the cavity charging efficiency will be around 24%, and will increase to 28% with a 2μs pulse. For a possible future system with a dedicated klystron and modulator, it's preferred to choose the pulse width according to the filltime, if pulsed heating is not a limiting factor.

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 $1{\times}10^7$ to fit with higher Q_0. Q_{ext} can be also adjusted by the step height between the sample and the bottom plate. The cavity is made of thinfilm niobium sputtered on copper. The sputtering will be done at CERN by S. Calatroni.

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].

FNAL Small Grain Niobium

We have tested a small grain Niobium sample provided by Lance Cooley of Fermilab.

The sample was first tested as received, without magnetic shielding. The Q_0 for the low power test is shown as the green curve in Fig. 4, and the green in Fig. 5 is the high power test Q_l (loaded Q). The residual resistance is approximately 2mΩ, which is extremely high for a superconductor, 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, with some improvement shown in the blue line in Fig. 4, but the sample still has significant residual resistance.

To reduce the residual resistance, we tried to clean the sample 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. We did not use BCP because we need to preserve the surface finishing of all the samples as received. The baked sample is tested with magnetic shielding. The test results are shown in the red curves in Fig. 4 and Fig. 5. 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 is also reduced. The quenching field increased significantly to 120mT.

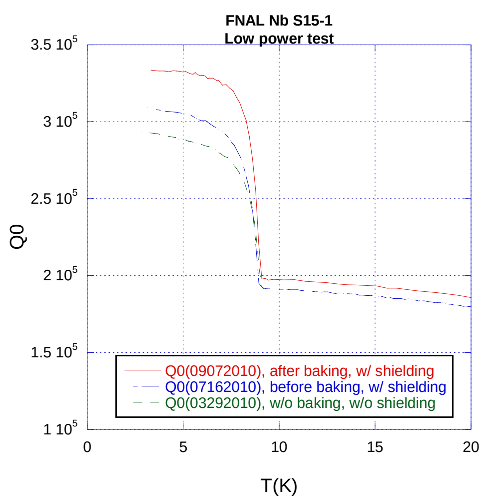

Figure 4: Low power test, FNAL small grain Nb

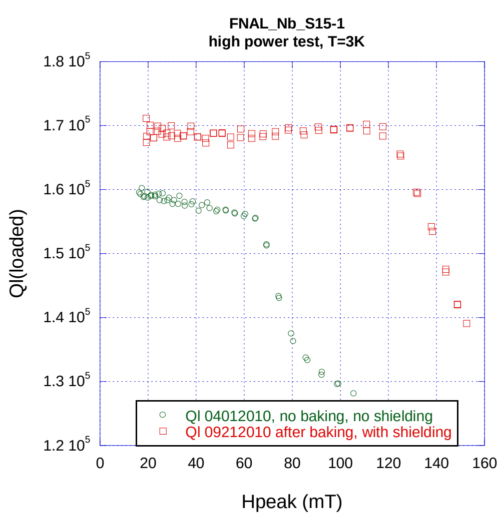

Figure 5: High power test, FNAL small grain Nb

LANL Single Grain CMP Niobium

A single grain niobium sample with CMP (chemical mechanical polish) 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 CMP was done by Cabot Microelectronics. The sample was tested with low power with different treatment and setup, with results shown in Fig. 6. Before cleaning/baking, the residual resistance in the superconducting state was about 6mΩ without magnetic shielding, about same as the resistance of copper; with magnetic shielding, the residual resistance reduced by about half. This residual resistance might be caused by the remnant of slurry used in the CMP process.

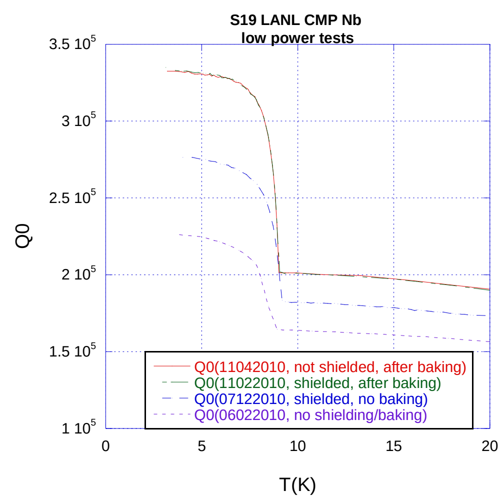

Figure 6: Low power test, LANL CMP Nb

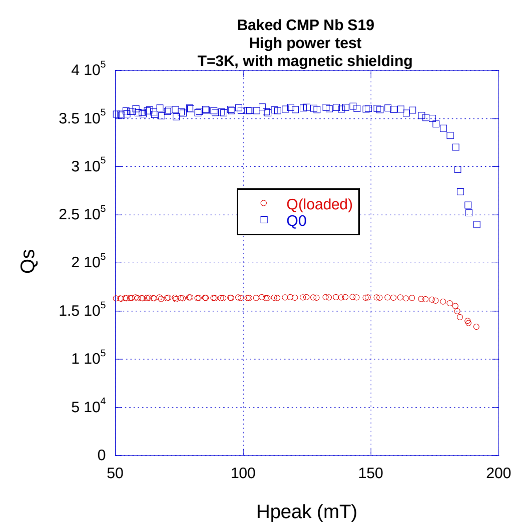

Figure 7: High power test, LANL CMP Nb

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 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. 7.

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 is more than 300mT, and is possible to enhance to 700mT or more. 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 considered low with the current copper cavity. A sputtered thin-film niobium cavity is under fabrication, which can significantly improve the precision of surface resistance measurement.

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.

ACKNOWLEDGEMENTS

The authors need to thank the SLAC Klystron Test Lab for providing the support for the experiments, especially the maintenance of the klystron system. We also owe our gratitude to Richard Talley and Robert Vanderzyl, for helping us changing the RF connection of the system from time to time. Lance Cooley and Tsuyoshi Tajima provided the niobium and MgB_2 samples. We also need to thank our colleagues Valery Dolgashev and Jim Lewandowski for all the support in this work. The work is supported by the US Department of Energy.

REFERENCES

[1] A. Gurevich, *Appl. Phys. Lett.* 88 012511, 2006

[2] T. Tajima, *Proceedings of the 15th International Conference on RF Superconductivity,* Chicago, IL USA (SRF2011)

[3] C. Nantista et al., "Test Bed for Superconducting Materials," *Proceedings of the 21st Particle Accelerator Conference (PAC05)*, Knoxville, TN, May 16-20, 2005, p. 4227.

[4] S. Tantawi et al., "Superconducting Materials Testing With a High-Q Copper RF Cavity," *Proceedings of the 22nd Particle Accelerator Conference (PAC07)*, Albuquerque, NM, June 22-26, 2007

[5] A. Canabal et al., "Critical Magnetic Field Determination of Superconducting Materials", *Proceedings of the EPAC08*, Genoa, Italy