ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK033

FIRST RF MEASUREMENTS OF PLANAR SRF THIN FILMS WITH A HIGH THROUGHPUT TEST FACILITY AT DARESBURY LABORATORY*

D. Seal[1,2] †, T. Sian[1,2], O.B. Malyshev[2,3], H. Marks[1,2], R. Valizadeh[2,3], P. Goudket[2,3,4], G. Burt[1,2]
[1]Engineering Department, Lancaster University, Lancaster, UK
[2]Cockcroft Institute, UKRI/STFC Daresbury Laboratory, Daresbury, Warrington, UK
[3]ASTeC, UKRI/STFC Daresbury Laboratory, Daresbury, Warrington, UK
[4]Now at European Spallation Source, Lund, Sweden

Abstract

The research on superconducting thin films for future radio frequency (RF) cavities requires measuring the RF properties of these films. However, coating and testing thin films on full-sized cavities is both challenging and time-consuming. As a result, films are typically deposited on small, flat samples and characterised using a test cavity. At Daresbury Laboratory, a facility for testing 10 cm diameter samples has recently been commissioned. The cavity uses RF chokes to allow physical and thermal separation between itself and the sample under test. The facility allows for surface resistance measurements at a resonant frequency of 7.8 GHz, at temperatures down to 4 K, maximum RF power of 1 W and peak magnetic fields of a few mT. The main advantage of this system is the simple sample mounting procedure due to no physical welding between the sample and test cavity. This allows for a fast turnaround time of two to three days between samples. As such, this system can be used to quickly identify which samples are performing well under RF and should require further testing at higher gradient. Details of recent upgrades to this facility, together with measurements of both bulk niobium and thin film samples, will be presented.

INTRODUCTION

Bulk niobium superconducting radio frequency (SRF) cavities are close to reaching their theoretical performance limits in terms of accelerating gradients and Q factors. As a result, there is a push to develop cavities using materials beyond Nb. These include, but are not limited to, Nb_3Sn, NbN, NbTiN, MgB_2. The materials are deposited as thin films, typically on copper cavities. The main reasons for this are: Cu is cheaper than Nb, it is more easily machinable and it benefits from a higher thermal conductivity.

The performance of thin films is usually studied on small, planar substrates. The main advantage over full cavity depositions is that small samples are much cheaper to produce and easier to deposit on. Also, some of the new materials being investigated are not yet developed enough to deposit on cavities. Having planar samples also allows for easier measurements under DC conditions and surface analysis techniques.

* This work has been supported by: the IFAST collaboration which has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730.
† daniel.seal@cockcroft.ac.uk

In order to study the performance of planar samples under RF conditions, a facility at Daresbury Laboratory has been developed over the past few years. This system allows us to measure the surface resistance, R_S, of small samples under RF conditions. The main advantage of this facility, compared with other RF testing facilities around the world [1], is the ability to test samples with a short two to three day turnaround time. This would importantly allow for the rate of sample characterisation to keep up with sample production.

The ultimate goal will be to follow up the sample tests with additional measurements using other facilities at Daresbury Laboratory. Future modifications to a magnetic field penetration facility on site [2] will allow testing of the same samples under DC conditions in order to obtain measurements of critical magnetic fields and relate the DC and RF superconducting properties. This, combined with surface analysis, will help identify the best performing thin films that will be worth up-scaling to full cavity tests.

This paper reports on the current status of the facility as well as sample measurements to demonstrate its capabilities.

FACILITY OVERVIEW

The test cavity used for studying the RF properties of planar samples, was first reported in [3]. The cavity itself is a bulk-Nb half cell (~ 31 mm diameter) surrounded by three quarter-wavelength chokes. The entire structure is 104 mm in diameter and 12 mm thick, shown in Fig. 1.

The cavity is mounted to an oxygen-free high conductivity (OFHC) Cu plate in a liquid helium (LHe) free cryostat cooled by a Gifford-McMahon cryocooler. This plate is able to reach a base temperature of 3.5 to 4 K. Details of this cryogenic facility can be found in [4]. A previous setup for this cavity used a LHe cryostat [5]. However, with a sample testing time of 2 weeks, this was considered to be too long, despite achieving lower base temperatures of 2.5 K. The LHe-free cryostat instead allows for a much faster sample testing time of just 2-3 days, not to mention the environmentally sustainable benefits from not using LHe supplies.

The choke structures allow for a small vacuum gap between the sample and cavity whilst minimising RF leakage. A 1 mm spacer made from G-10 is used to maintain this gap, allowing the two to be thermally and physically isolated. Therefore no welding is required between the sample and cavity. This is another reason why the system allows for easy sample changeover and short testing times.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK033

Separation of the cavity and sample allows for measurements of R_S using an RF-DC compensation method. A recent redesign of the sample holder, allowing for optimal control of the sample temperature, T_S, has enabled us to use this method. This technique utilises heaters and Cernox thermometers connected to the sample holder in order to measure the change in DC heater power required to maintain a stable T_S after RF is switched on. This change in heater power is equivalent to the RF power dissipated on sample, from which the average R_S of the sample is measured. This method fully described in [6].

The facility, up until recently, only used a single coupler. The stored energy, U, required for measuring the surface magnetic field on the sample, $B_{S,pk}$, was measured from the reflected S_{11} signal. However, this method relied on a large number of cable calibrations in order to calculate the forward power into the cavity, introducing additional errors. To overcome this and improve the accuracy of measurements of U, the system has been slightly modified in order to facilitate a pickup coupler. This will enable measurements of transmitted power and directly determine U. This also provides more accurate measurements of $B_{S,pk}$. Simulations in CST [7], showed that the pickup coupler could be positioned in the middle or outer chokes surrounding the cavity whilst minimising the radiation leakage. These positions also avoid the formation of fano resonances which occur due to the interference between the fundamental cavity mode frequency and nearby choke mode frequencies. The modified cavity and facility illustrating the positioning of the pickup probe is shown in Fig. 1.

Overall, the facility is currently able to make measurements of R_S at a resonant frequency, f_0 = 7.8 GHz, T_S from 4 to 10 K and $B_{S,pk} \leq 0.8$ mT. It can measure R_S versus $B_{S,pk}$ at constant T_S as well as R_S versus T_S at constant $B_{S,pk}$.

FACILITY COMMISSIONING

Bulk Nb Sample

During commissioning, the facility has demonstrated that both the sample and cavity can reach a minimum T_S = 3.9 K after approximately 12 hours of cooling. After some adjustments to the RF system, a maximum $B_{S,pk} \approx 0.8$ mT was reached.

The easiest way to demonstrate the capabilities of the facility was to test a bulk Nb sample. This also provides a baseline for future thin film sample measurements. The sample tested was approximately 100 mm in diameter, 50 mm thick and had a $RRR \approx 400$. Also, it had not received any surface treatments or high pressure rinse pre-testing.

Measurements of R_S vs T_C/T_S for this sample are shown in Fig. 2, where T_C is the critical temperature (T_C = 9.2 K for Nb). Due to the current lack of a chemical treatment facility at our lab, it was decided to repeat the measurements on this sample with different sample treatments to see which would provide the lowest R_S and indicate whether our measurement procedure is sensitive to different sample treatments. The treatments tried were de-grease with isopropanol (A), de-grease with acetone followed by an ultra-pure water (UPW) bath (B) and 600 °C bake (C).

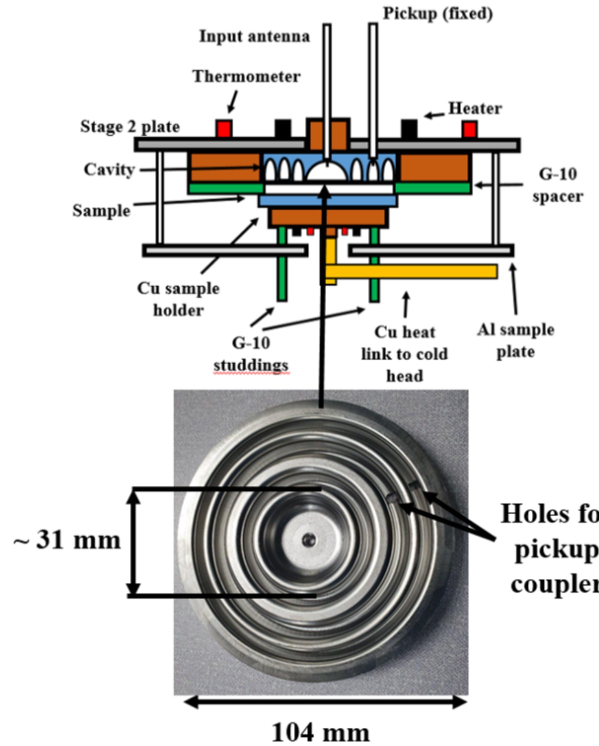

Figure 1: A schematic showing the mounting of the cavity and sample to the stage 2 plate of the cryostat. The choke cavity is shown underneath indicated holes drilled in the middle and outer chokes for pickup coupler insertion.

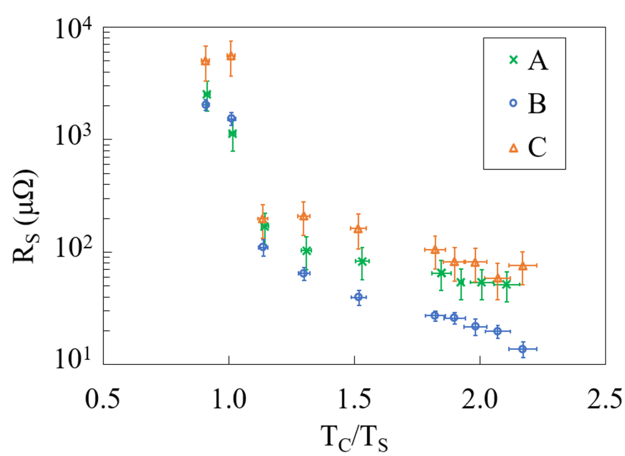

Figure 2: R_S vs T_C/T_S at constant $B_{S,pk}$ = 0.45 mT. A - de-grease with isopropanol, B - de-grease with acetone followed by an UPW bath and C - 600 °C bake.

At 4.2 K, a theoretical BCS resistance of ≈ 15 μΩ is expected for the Nb sample tested. The results shown in Fig. 2 indicate a clear difference in R_S between each of the treatments. The de-grease with acetone followed by an

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK033

ultra-pure water rinse shows the lowest R_S and hence the lowest residual resistance. The treatment with isopropanol has increased R_S due to the formation of a lossy film on the Nb surface. Also, any treatment with a solvent should be followed with an UPW bath to remove any solvent remaining on the surface. Finally, the 600 °C bake results in trapped hydrogen on the surface resulting in increased losses as well. The aim will be to repeat these measurements after buffered chemical polishing to remove the hydrogen layer.

Whilst commissioning the facility, measurements of R_S vs $B_{S,pk}$ at fixed temperature have also been demonstrated, as shown in Fig. 3. These measurements show consistent values of R_S at low $B_{S,pk}$ as expected. Due to microphonics and laboratory radiation controls, the facility is currently limited to low $B_{S,pk}$. A phase-locked loop control system is in the process of being implemented to overcome the limitations caused by microphonics.

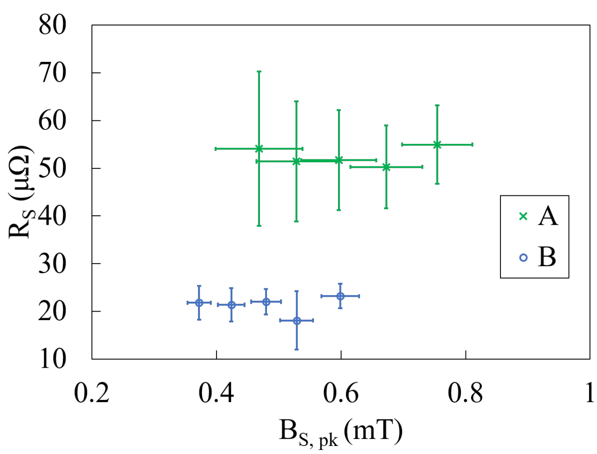

Figure 3: R_S vs $B_{S,pk}$ at T_S = 4.6 K. A - de-grease with isopropanol, B - de-grease with acetone followed by an UPW bath.

With this facility, the shift in resonant frequency, Δf, can also be resolved as a function of T_S. This is shown in Fig. 4. It demonstrates the sharp decrease in resonant frequency around T_C due to the sample becoming normal conducting.

Nb on Cu Samples

In addition to measuring bulk Nb, two Nb on Cu samples were tested for the first time. Both films were deposited by pulsed DC magnetron sputtering onto 100 mm diameter Cu disks which were mechanically polished with a diamond abrasive. Sample 1 was deposited after heating to 600°C and sample 2 at room temperature. Measurements of R_S vs T_C/T_S are shown in Fig. 5.

The purpose of these tests were mainly to show that the facility could measure thin films as well as bulk samples. The R_S measurements of the two samples are comparable to the lowest bulk Nb R_S measurements from Fig. 2. Both samples exhibit rapid increases in R_S at T_C (T_C/T_S = 1) as expected. The results also show that R_S is slightly lower for sample 2 compared to sample 1 over the temperature range.

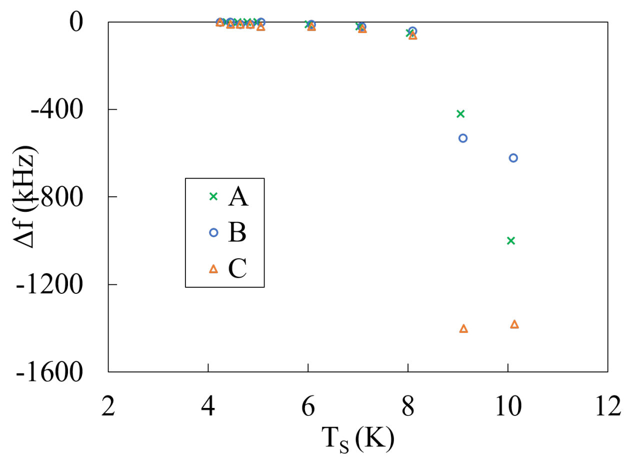

Figure 4: Δf vs T_S.

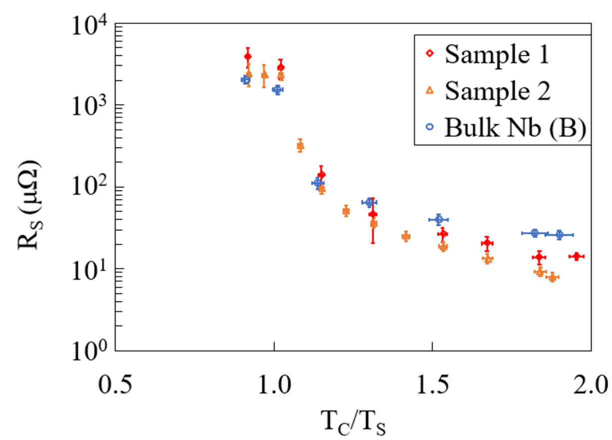

Figure 5: R_S vs T_C/T_S for the two Nb on Cu samples at constant $B_{S,pk}$.

Though Surface analysis of these two samples has yet to be made to investigate the difference. It should also be noted that the sample heater power and temperature stabilise in a much shorter time for Cu samples compared with bulk Nb. The Cu samples also have smaller errors on T_S due to a higher thermal conductivity and hence a better thermal contact with the sample holder.

CONCLUSIONS

The capability to measure R_S of flat samples under RF conditions has now been demonstrated using both bulk Nb and Nb on Cu samples. By operating in a LHe-free environment, samples can be tested down to T_S = 4.1 K and $B_{S,pk} \leq$ 0.8 mT. As a result, the facility will be a useful tool to study thin film samples under RF conditions at a rate of 2 to 3 sample tests per week.

Further improvements are ongoing, however these will not affect any current sample tests. The main improvement will be the addition of a phase-locked loop control system. This will utilise the newly installed pickup coupler by locking the input on resonance whilst aiming to remove the effects of microphonics. It will allow for critical coupling of the input antenna resulting in higher $B_{S,pk} \leq$ 10 mT.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK033

ACKNOWLEDGEMENTS

The authors wish to acknowledge support received by members of ASTeC, namely J. Conlon, A. May, S. Hitchen, K. Dumbell, D. Turner and L. Smith. We also wish to acknowledge work carried out by staff in the Engineering Technology Centre at Daresbury Laboratory. D. Seal would like to thank UKRI for his PhD funding and T. Sian for his STFC/Cockcroft Institute grant.

REFERENCES

[1] P. Goudket *et al.*, "Devices for SRF material characterization," *Superconductor Science and Technology*, vol. 30, no. 1, p. 013 001, 2016, doi:10.1088/0953-2048/30/1/013001

[2] D. Turner *et al.*, "Magnetic Field Penetration of Niobium Thin Films Produced by the Aries Collaboration," in *Proc. SRF 2021, East Lansing, MI, USA*, 2021, pp. 77–81, doi:10.18429/JACoW-SRF2021-SUPFDV007

[3] P. Goudket *et al.*, "Superconducting Thin Film Test Cavity Commissioning," in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, pp. 731–734, https://jacow.org/SRF2015/papers/TUPB064.pdf

[4] O. B. Malyshev, G. Burt, J. A. Conlon, P. Goudket, N. Pattalwar, and S. M. Pattalwar, "The SRF Thin Film Test Facility in LHe-Free Cryostat," in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 610–612, doi:10.18429/JACoW-SRF2019-TUP070

[5] P. Goudket *et al.*, "First Full Cryogenic Test of the SRF Thin Film Test Cavity," in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 644–646, doi:10.18429/JACoW-SRF2017-TUPB104

[6] D. Seal *et al.*, "A Low Power Test Facility for SRF Thin Film Testing with High Sample Throughput Rate," in *Proc. SRF'21*, East Lansing, MI, USA, 2021, pp. 100–104, doi:10.18429/JACoW-SRF2021-SUPFDV016

[7] *CST Studio Suite*, https://www.3ds.com/products-services/simulia/products/cst-studio-suite/.