ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-MOPMB001

DEVELOPMENT AND TESTING OF SPLIT 6 GHz CAVITIES WITH NIOBIUM COATINGS*

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Abstract

Superconducting thin-films on a copper substrate are used in accelerator RF cavities as an alternative to bulk Nb due to the high thermal conductivity of copper and the lower production costs. Although thin-film coated RF cavities can match, or even exceed the performance of bulk Nb, there are some challenges around the deposition. The RF cavities are often produced as two half-cells with a weld across the centre where the RF surface current is highest, which could reduce cavity performance. To avoid this, a cavity can be produced in 2 longitudinally split halves, with the join parallel to the surface current. As the current doesn't cross the join a simpler weld can be performed far from the fields, simplifying the manufacturing process, and potentially improving the cavities performance. This additionally allows for different deposition techniques and coating materials to be used, as well as easier post-deposition quality control. This paper discusses the development and testing of 6 GHz cavities that have been designed and coated at the Cockcroft Institute, using low temperature RF techniques to characterise cavities with different substrate preparations and coating techniques.

INTRODUCTION

Niobium (Nb), which is commonly used for accelerating cavities, is expensive and has a low thermal conductivity at cryogenic temperatures. The low thermal conductivity can lead to localised heating, leading to a quench. In order to avoid this, a thin superconducting film can be deposited onto a copper (Cu) substrate, which utilises the high thermal conductivity of copper, while maintaining the benefits of a SRF cavity. Modern research is also beginning to reveal a number of other superconductors that would not be suitable for application as a bulk superconductor, due to physical properties, such as brittleness, but can match, or even exceed the performance of niobium when it is used in thin film applications. These include Nb_3Sn, NbTiN, and V_3Si [1].

Most commonly, RF cavities are produced as 2 half cells, known as cups, which are then e-beam welded together around the equator. This weld occurs across the region where the magnetic field and surface current is highest, which research on ISOLDE is showing may result in lowered performance[2]. In addition when using thin films, this weld is an area where micro cracks can occur, which can also reduce the Q-factor of the cavity. One solution to this has been to produce a seamless cavity, however this is expensive and creates a more challenging deposition process as the target must be located on the inside of the cavity for deposition.

At the Cockcroft Institute, a novel longitudinally split cavity geometry has been developed, which is constructed from 2 half cells split longitudinally, rather than transversely, such that the surface current runs along, rather than across, the seam. As such the cavity may be operated with a gap between the two half-cells and so a any weld can be located far from the RF surface, and can hence be applied after coating. The open design also allows for planar thin film deposition techniques as well as surface characterisation prior to welding making research and development of thin-film superconductors much simpler [3, 4].

Simultaneously at CERN, a similar cavity known as a Slotted Waveguide ELLiptical cavity is under development for potential use on the FCC. SWELL cavities are manufactured in 4 quadrants rather than 2 longitudinally split half-cells with HOM dampers placed in the gaps between sections [5].

This paper describes the process for designing and testing the cavities that have been produced at the Cockcroft Institute. The aim is to compare the RF surface resistance (R_s) for different Nb coatings, that were performed using various deposition parameters, and look at the effect of electropolishing (EP) on the cavity performance.

CAVITY DESIGN USING CST AND MANUFACTURE

The cavity was designed in CST [6]. It has an elliptical geometry, with a resonant frequency, f_0 = 6 GHz. The shape was chosen for this first iteration simply due to it being a standard cavity shape. The coupling pipe was made long to reduce any losses from the end plates. In the future an optimization process will be performed in order to improve the cavity for the longitudinal design. Figure 1 shows the E field for the current cavity geometry.

The present design has a coupling pipe radius = 14 mm, equator = 22.95 mm, and the length of the coupling pipes = 80 mm. Using these parameters, simulations predict a maximum magnetic field strength = 3.66 mT with 0.1 mJ of stored energy.

The cavity is formed from 2 Cu blocks, which can be accurately aligned with each other using 2 pins and then bolted together with 4 bolts. The cuboid shape provides good me-

* 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.
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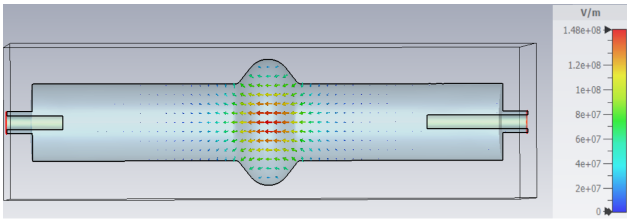

Figure 1: The cavity shape modelled in CST [6] showing the E-field.

chanical stability. The high thermal mass and high thermal conductivity of Cu provide high temperature uniformity and stability. The flat outer surface is also good thermal contact and convenient mounting surface to attach thermometers and heaters along the cavity. The antennas are attached via Cu end plates that are bolted into the cavity itself using 4 holes. The input coupler protrudes 30 mm into the coupling pipe, and the pickup coupler protrudes 12 mm into the coupling pipe.

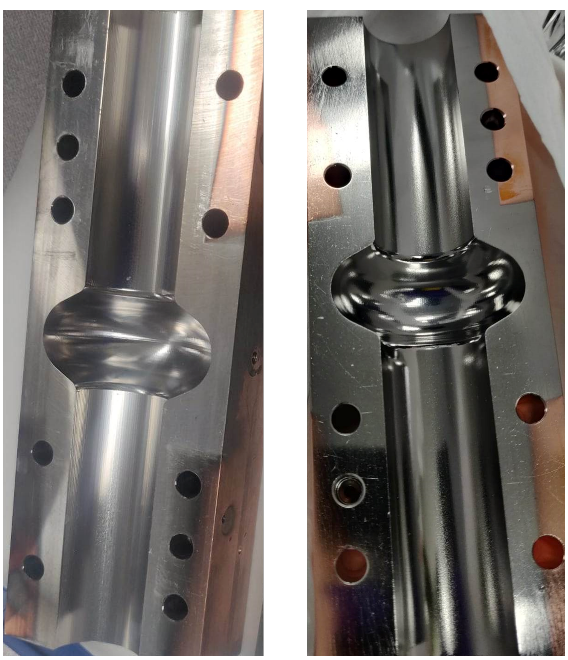

Figure 2: Cavity A (left), that was mechanically finished only, with the 3rd Nb coating, and cavity B (right) after EP and coating with Nb.

Three cavities (A,B and C) have been manufactured at the Cockcroft Institute. Each was machined initially using a 10 mm bore nose at 6000 rpm, and then again with a 5 mm bore hole at 45000 rpm to provide a smoother internal surface finish. Two of the cavities (B and C) were then sent for EP at LNL/INFN. The electropolishing parameters can be found in Ref. [3]. In Fig. 2 the machine finished cavity, cav A, can be seen on the left, and the electropolished cav B is shown on the right.

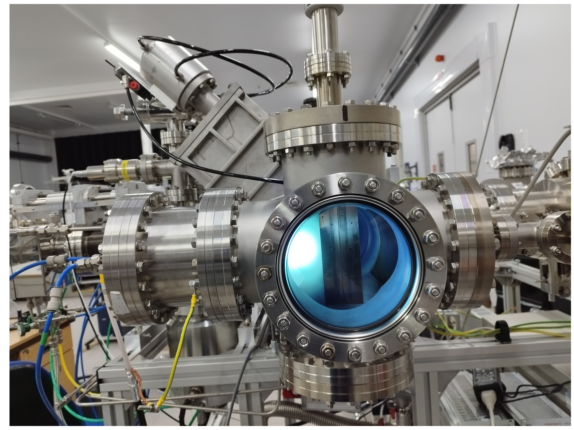

Figure 3: One of the Nb depositions on cavity A.

Nb COATINGS

After machining and polishing, a Nb thin film was deposited onto each the cavities in house. The cavities were each sputtered from a Nb target. Three depositions have been performed on cavity A - the unpolished cavity. Throughout the paper these will be referred to as cav A (1), cav A (2) and cav A (3). This refers to the order in which they were deposited. Cav A (1) and cav A (2) were sputtered with a cylindrical magnetron, and cav A (3) and cav B was sputtered with a planar magnetron. The change was made in order to be able to use a higher purity Nb target, and so as to be able to make direct comparisons with planar samples measured with a choke cavity [7] as well as future depositions on Nb_3Sn and NbTiN, since they will also be deposited with a planar target.

The first coating of cav A (1) was performed at room temperature, with the cavity oriented face to face and the cylindrical Nb magnetron, with permanent magnet at its centre. Subsequently, the cavities were coated facing outwards with the planar magnetron in order to have better control and monitoring of the deposition, shown in Fig. 3.

Cav A (3) was deposited at increased temperature - between 300 – 400°C and a total deposition time for 2 hours for each half. A target power of 300 W was used for the duration. The voltage was between 190 and 200 V and the current used was between and 1.5 and 1.58 A for the duration of the deposition. Cav B was also deposited at the increased temperature, with a total time of 90 minutes for each half. The setpoint used for cav B was 301 W, with a voltage of between 229 and 236 V, and current of between 1.31 and 1.28 A.

CRYOSTAT SETUP

The cooling system used for the 6 GHz cavity at the Daresbury Laboratory is a 2-stage liquid helium free cryostat, that uses a SHI Cryogenics RDK-415D2 cold head with a 1.5 W capacity at 4.2 K. A liquid helium system would provide a higher cooling capacity, however this requires a ready supply of liquid helium and the cavity would need to be welded for testing which would greatly increase the time taken to

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test new thin films, and introduces the risk of damaging the cavity.

The system was initially designed for use with a choke cavity for planar sample testing [8]. It has been adapted to also house the 6 GHz split cavity, meaning both can be installed simultaneously, thereby minimising the amount of time required to cool and warm up the system.

The cavity is attached vertically to the cold head (as shown in Fig. 4) with a Cu base plate and 2 vertical Cu plates that are used to bolt along the cavity length. Two Cernox thermometers are attached to the outside of the cavity – one on each half, on opposing sides using M3 screws. Four 10 Ω (12.5 W) heaters (Vishay, USA) are also used, arranged so as to have 2 on each half with one on each side of the cavity to ensure uniform heating.

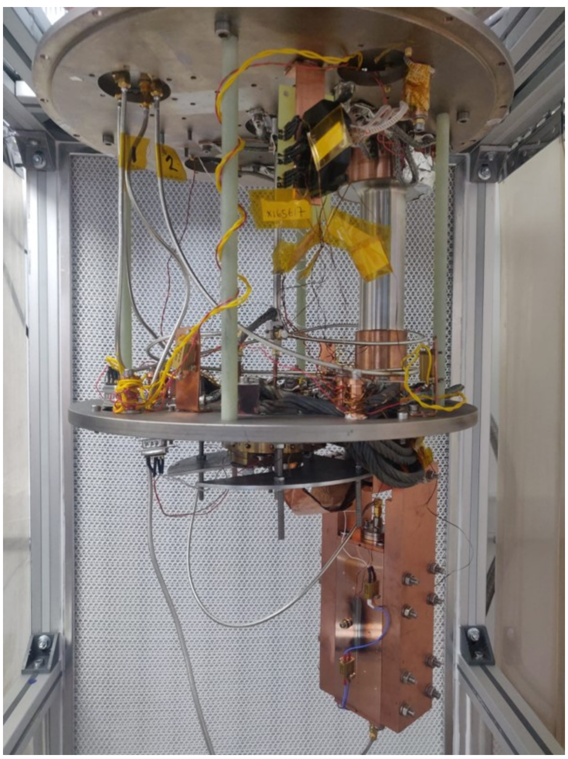

Figure 4: One of the cavities installed vertically in the cryostat.

MEASUREMENT TECHNIQUES

Measurements of R_s were taken at temperatures from 4 – 10 K. Each cavity was measured using a vector network analyser (VNA) used to send a low power RF signal (up to 10 dBm) to the input coupler.

The scattering parameters (S-parameters) are measured (S_{11} and S_{21}). $|S_{21}|$ is used to calculate the 3 dB bandwidth S_{11} for the coupling factor (β). Q_0 is found by calculating the loaded Q factor (Q_L) from S_{11}. The resonant frequency (f_0) is found where the $|S_{21}|$ frequency is maximum. The system is a 2 port system, however the the transmitted coupling is very week ($\beta \ll 1$, or Q_t is very high), so β_t can be considered negligible.

Using S_{11max} and S_{11min}, or the maximum and minimum reflected power across the frequency span at a given input power, β can be calculated using:

$$\beta = \frac{S_{11max} - S_{11min}}{S_{11max} + S_{11min}}, \tag{1}$$

where β is the external coupling factor, loaded Q factor is the Q factor for the system, including the couplers, and can be found by finding the ratio between f_0 and the 3 dB bandwidth (Δf):

$$Q_L = \frac{f_0}{\Delta f}. \tag{2}$$

From these it is possible to find the intrinsic quality factor of the cavity, Q_0:

$$Q_0 = Q_L(1 + \beta). \tag{3}$$

Finally, R_s is found

$$R_s = \frac{G}{Q_0}, \tag{4}$$

where G is the geometry factor and is found via simulations in CST [6].

These measurements are repeated in steps of 0.5 K assessing from 4 K, to approximately 8 K, where it is expected that the superconducting transition may start to occur, and then in steps of 0.2 K to approximately 10 K, or the point where the R_s can be seen to level off.

RESULTS

In order to test the initial design of the split cavity, and developments in the coating methods, 4 cavity tests were compared, all with a Nb coating. Through improved coating methods R_s on cavity A was improved from 532 µΩ on the first test, to 131 µΩ on the most recent cavity test, both at 4.2 K. The 4th test has been completed on cavity B, which received an EP before deposition, and provided the best results to date, as can be seen in Fig. 5. The Surface resistance for Cav B is shown with the BCS resistance on Fig. 6. This shows promising improvement, and through continuous refining of the deposition techniques, and future redesign of the cavity geometry. it is anticipated that significant further improvements will be possible.

The surface resistance was measured Nb coated cavites at 4.2 K and found to be 532 ± 10 µΩ for cavity A(1), 393 ± 6 µΩ for cavity A(2), 131 ± 5 µΩ for cavity A(3) and 70 ± 5 µΩ for cavity B.

T_c was measured at the point where the resistance begins to level off and was found to be around 8.4 ± 0.3 K for cavity A(1), 8.8 ± 0.2 K for cavity A(2), 9.3 ± 0.2 K for cavity A(3) and 9.4 ± 0.2 K for cavity B. Since the expected T_c for Nb is around 9.2 K, this is slightly lower than expected for cavities A(1) and A(2), but within an acceptable range for the other coating, along with the Surface resistance and critical temperature in Table 1.

The R_s results for cavity B were plotted along with a BCS resistance calculated using SRIMP [9].

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Table 1: Surface Resistance Measurements at Each Stage of Polishing for Uncoated Cavities

Cavity	Film	Deposition facility	Finish	Condition	R_s at 4.2 K (μΩ)	T_c (K)
A(1)	Nb	Cylindrical Magnetron	Mechanical finish	room temperature, cavity halves facing together with target in centre	532 ± 10	8.4 ± 0.3
A(2)	Nb	Cylindrical Magnetron	Mechanical finish	room temperature, cavity halves facing together	393 ± 6	8.8 ± 0.2
A(3)	Nb	Planar Magnetron	mechanical finish	300-400°C, cavity halves facing outwards	131 ± 5	9.3 ± 0.2
B	Nb	Planar Magnetron	Electro polish	300-400 °C, cavity halves facing outwards	70 ± 5	9.4 ± 0.2

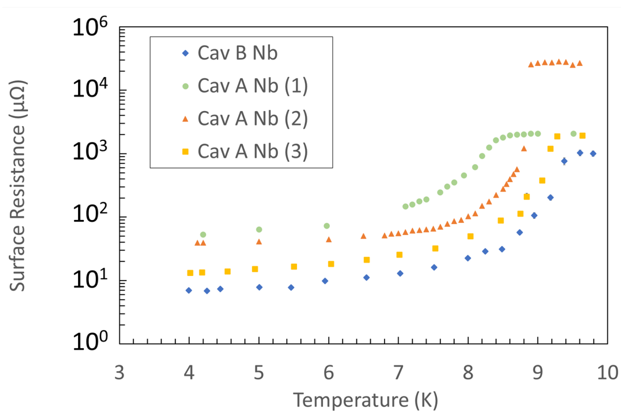

Figure 5: Surface Resistance for cavites A(1), A(2), A(3) and B, all coated with Nb.

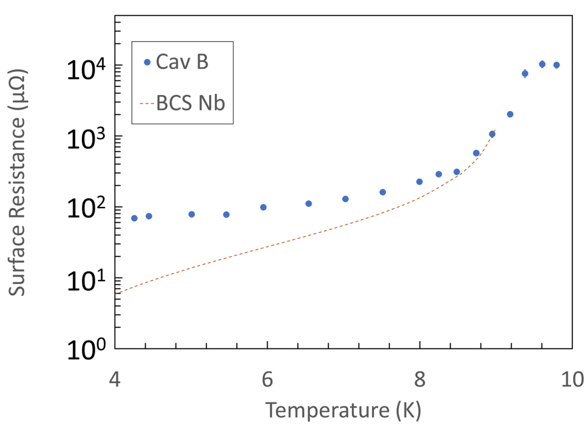

Figure 6: Surface resistance of Nb cavity B compared to BCS resistance calculated using SRIMP [9] with parameters: f_0 = 6 GHz, T_c = 9.2 K, $\Delta/k_B T_c$ = 1.86, λ_L = 33 nm, ξ_L = 40 nm, RRR = 2.

DISCUSSION

Over the course of 3 tests, R_s has been improved by a factor of 4.

Each of the cav A coatings performed better than the predecessor as the deposition process has been improved through the use of higher temperatures, better quality targets, and orienting the cavities outwards so as to have better control over deposition.

A superconducting to normal conducting transition can be seen for each of the cavities, although there is some variation in the value of the critical temperature, likely due to impurities in the coating.

After each deposition of cav A the film was removed mechanically and so the internal size of the cavity increased with each deposition. The surface finish of the cavity A before each deposition is likely to be consistant as the same machining tool was used at the same speed (45000 rpm) each time.

Cav B had a lower R_s than cav A after depositon of Nb with the same parameters, this can be attributed to the smoother surface of the cavity B after electropolishing.

The surface resistance for Cav B levels off at lower temperatures, suggesting that there is a residual resistance. This could be due to a number of things, including impurities in the coating and cavity geometry.

CONCLUSION AND FUTURE DEVELOPMENT

Surface resistance measurements have been measured for 4 different Nb coatings on 2 different cavities, and show continuous improvement as the deposition methods are improved. Electropolishing of the surface improved the surface resistance further, resulting in a current lowest surface resistance of 70 μΩ at 4.2 K.

This demonstrates the potential of the split cavity design, and future upgrades to the cavity design have the potential to further improve on what has already been measured. Some suggested upgrades include redesigning the antenna end plates and adding a rounded edge to the cavity, in order to minimise alignment issues, as well as a full optimisation of the cavity geometry. A rounded edge will also be added to a third cavity - cav C, which is hoped will reduce the effects of misalignment.

In addition, movement to a new radiation test bunker where will be allow operation at higher RF powers, thus the effect of higher RF fields to be measured.

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In future, alternative superconducting coatings, such as V_3Si, will be tested on these cavities. These materials have the potential to provide higher Q factors and outperform Nb at higher temperatures.

ACKNOWLEDGEMENTS

G. Burt, N. Leicester, D. Seal and H. Marks would like to acknowledge that their contribution to this work was funded by STFC via the IAA award to Lancaster University, and the Cockcroft Institute core grant.

REFERENCES

[1] C. Benjamin *et al.*, "Deposition and Characterisation of V_3Si films for SRF Applications," presented at SRF'23, Grand Rapids, MI, USA, June 2023, this conference.

[2] W. V. Delsolaro and A. Miyazaki, "Seamless Quarter Wave Resonators for HIE ISOLDE," in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 292–296. doi:10.18429/JACoW-LINAC2018-TU1A05

[3] B. S. Sian *et al.*, "Split Thin Film SRF 6 GHz Cavities," in *Proc. LINAC'22*, Liverpool, UK, 2022, pp. 814–817. doi:10.18429/JACoW-LINAC2022-THPOGE09

[4] B. T. Sian *et al.*, "Split 6 GHz SRF thin film cavities," presented at IPAC'23, Venice, Italy, May 2023, paper WEPA185.

[5] F. Peauger *et al.*, "SWELL and Other SRF Split Cavity Development," in *Proc. LINAC'22*, Liverpool, UK, 2022, pp. 300–304. doi:10.18429/JACoW-LINAC2022-TU1AA04

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

[7] D. Seal *et al.*, "Optimisation Of Niobium Thin Film Deposition Parameters For SRF Cavities," presented at SRF'23, Grand Rapids, MI, USA, June 2023, this conference.

[8] O. B. Malyshev, P. Goudket, N. Pattalwar, S. Pattalwar, J. Conlon, and G. Burt, "The srf thin film test facility in lhe-free cryostat," in *Proc. SRF'19, Dresden, Germany*, pp. 612–614, 2019.

[9] M. Liepe. "SRIMP." (2012), https://www.classe.cornell.edu/~liepe/webpage/researchsrimp.html