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SPLIT THIN FILM SRF 6 GHz CAVITIES

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Abstract

Radio-frequency cavities used in particle accelerators are usually manufactured from two half cells that are electron beam welded together. In this case, the weld is located across the peak surface current of the cavity. This weld can lead to large increases in surface resistance and limit the performance of thin film coated cavities. Many problems with the coating process for thin film Superconducting Radio Frequency (SRF) cavities are also due to this weld. Thin film SRF cavities can perform as well as bulk niobium cavities if the cavity is manufactured seamlessly, without any weld, as they have a more uniform surface, however, they are much more difficult and expensive to manufacture. A cavity with a longitudinal split, parallel to the direction of the electric field, would not need to be welded. These seamless cavities are easier to manufacture and coat. This opens the possibilities to coat with new materials and multilayer coatings. These cavities may allow SRF cavities to operate at significantly better parameters (higher quality factor and maximum accelerating field) than current state of the art cavities. This work discusses development and testing of longitudinally split seamless cavities at Daresbury Laboratory (DL).

INTRODUCTION

The advantages of SRF cavities are that they have a much lower surface resistance when superconducting (usually bulk niobium cavities have a surface resistance of 10^4 to 10^6 lower than bulk copper cavities [1]), which means that less heat is lost in the walls of the cavity. This leads to the fact that they can be run in continuous operation at high accelerating gradients [1–3], when the resistive losses in copper at high gradients can lead to melting of the cavity.

The main issue with using bulk super conducing cavities is that they have a lower thermal conductivity than copper cavities which can lead to localised heating and therefore, that can cause a small area of the superconductor to become normal conducting, when this happens the rest of the superconducting material quickly follows and becomes normal conducting, this is called a quench [2, 3]. The idea of coating the inside of a copper cavity with a thin film of a super conductor has been in development for many decades [2, 3]. The driving principle is that the copper cavity can provide better thermal conductivity than niobium spreading any localised heating on the superconductor to the rest of the cavity while the charge in the cavity is carried by the superconducting thin film [2, 3]. Another advantage of thin films is that materials that are too brittle to be formed into cavities, and have better superconducting properties than niobium, can be coated onto a copper cavity and, perform just as well if not better than pure niobium. Some such materials include Nb_3Sn [4], MgB_2 [5] and V_3Si. Superconducting thin films have been used in several accelerators including PIAVE-ALPI at INFN [6] HIE-ISOLDE [7, 8], LEP [7, 9] and the LHC [7, 10].

A well known technique to manufacture RF cavities is to create two half cells and then use electron beam welding to join them. The main problem with this method of manufacture is that the weld, as it is around the area of highest magnetic field and highest surface current in the cavity which results in a higher resistance of the cavity. The weld also leads to problems with cavities coated with superconducting thin films. The cavities for HIE-ISOLDE for example found micro cracks around the weld, these cavities had a large decrease in quality factor as the accelerating gradient increased. Seamless cavities were then manufactured and coated and the Q-slope was reduced [11]. Longitudinally split SRF cavities are also currently in development at CERN, Slotted ELLiptical (SWELL) cavities are the baseline solution the Future Circular Collider (FCC). Because the welds will be in the Higher Order Mode (HOM) dampeners, they will be away from electric field of TM11 mode [12], however, SWELL cavities have not been manufactured or tested as of yet.

This work describes design, manufacture, coating and testing of seamless split niobium coated copper cavities at DL. The cavities were designed to be seamless so no weld was required and they were designed to be split so that they could be coated in an open geometry, this also allowed for easier access to the coated cavity for surface analysis.

CAVITY MANUFACTURE AND COATING

Three Oxygen Free High Conductivity (OFHC) copper cavities were designed using CST Microwave Studio. The cavities were designed to be TESLA shaped with a resonant frequency of 6 GHz. The peak electric field was simulated to be 150 MeV/m and the peak magnetic field was simulated to be 0.37 T with 1 J of stored energy. The body of the cavity was designed to be a cuboid shape to provide a simple geometry for attaching thermometers, heaters and heat links. The shape also provided a large thermal mass which aided temperature stability. At the small ends of the cavity four M6 holes were made to allow mechanically stable attachment of the antennas to the cavity to reduce microphonics from the pulsing of the cold head.

The cavities were manufactured in house at DL using a tungsten carbide milling tool. The milling tool for the initial manufacture had a 10 mm bore nose at a speed of 6000 RPM (the fastest speed it could be used). The first

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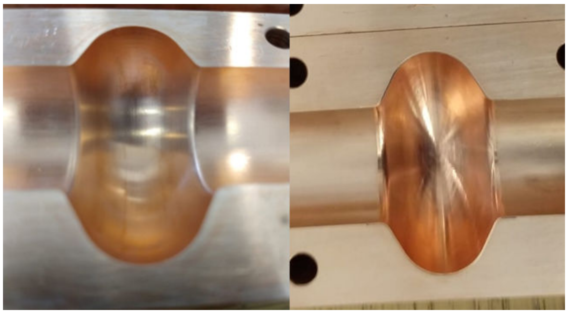

Figure 1: Cavities machined with the initial machining tool and parameters (left) and the second machining tool (right).

measurements of the surface resistance were made after the initial machining. The cavities were then cleaned in an ultrasonic bath with acetone for 15 minutes and surface resistance measurements were made again. The surface resistance of the cavities were then measured at 4 K. The cavities were re-machined using a 5 mm bore nose at a speed of 45000 RPM providing a smoother finish and the cleaning and measurement process was repeated. Images of the cavity after each stage of machining can be found in Fig. 1 it can be seen that the finish is more reflective after machining with the smaller, faster bore nose.

After the second machining, cavity ‘A’ was cleaned, tested then coated in two parts using pulsed DC sputtering of a pure niobium target without any further polishing. The sputtering was performed with a 300 W pulse with 2.10 A, 143 V. The pulse frequency was 350 kHz, the dual time was 1.1 µs for 3 hours at 3.85×10^{-2} mbar of krypton at room temperature (RT). An image of the cavity after coating can be seen in Fig. 2.

Figure 2: Cavity A coated with niobium.

SURFACE RESISTANCE MEASUREMENTS

The surface resistance was calculated from the Scattering (S) parameters of the cavity. The S-parameters were measured using two antennas connected to a Vector Network Analyser (VNA). The antennas were connected to the cavity using a mini conflat feedthrough and an OFHC copper adapter piece designed in house. Traces of the S11 and S21 parameters with a span of 20 MHz were taken. The bandwidth was then measured using the 3 dB points below the resonant frequency of the S21 trace. The loaded quality factor, Q_l, was then calculated using:

$$Q_l = \frac{\omega_0}{\Delta\omega}\,, \tag{1}$$

where, ω_0, is resonant frequency and, $\Delta\omega$, is the bandwidth. The beta (coupling) of the cavity was calculated from the S11 trace. using the formula:

$$\beta = \frac{S_{11\text{max}} - S_{11\text{min}}}{S_{11\text{max}} + S_{11\text{min}}}\,, \tag{2}$$

where $S_{11\text{min}}$ and $S_{11\text{max}}$ are the minimum and maximum values of the S11 parameters in dB.

The quality factor, Q_0, of the cavity was then calculated using:

$$Q_0 = \frac{Q_l}{1+\beta}\,. \tag{3}$$

The surface resistance, R_s, was then calculated using:

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

where the geometry factor, G, was taken from a CST microwave studio simulation of the cavity.

CRYOGENIC MEASUREMENT FACILITY

To cool down the cavity to cryogenic temperatures a SHI Cryogenics RDK-415D2 cold head was used. A cold head system was chosen as the measurements required are at low power which was achievable with a lower running cost using a cold head system rather than using liquid helium. The first stage of the cold head was connected to a heat shield in order to reduce the thermal radiation onto the cavity. The cavity was connected to the cold head using two 20 mm thick copper bars. Figure 3 shows the cavity mounted onto the cold head. These copper bars were bolted onto the cavity, indium was used between each connection to provide good thermal contact. The cavity reached 4.2 K after 12 hours of cooling. The cold head was operated in a vacuum vessel with a base pressure of 10^{-6} mbar when cold.

RESULTS AND DISCUSSION

Normal Conducting Results

Measurements were performed at RT before and after each stage of cleaning and polishing. Measurements were also made at 4.2 K after each clean. The surface resistance of each cavity at each stage can be found in Table 1.

The surface resistance decreased after polishing each cavity which was expected. However, this surface resistance is higher than ones measured at OFHC copper surfaces SLAC. SLAC measured R_s of a 5.7 GHz copper cavity to be 1.6×10^{-2} Ω at RT and 4×10^{-3} Ω at 4.2 K [13]. Thus, our best results for mechanically polished cavity surfaces

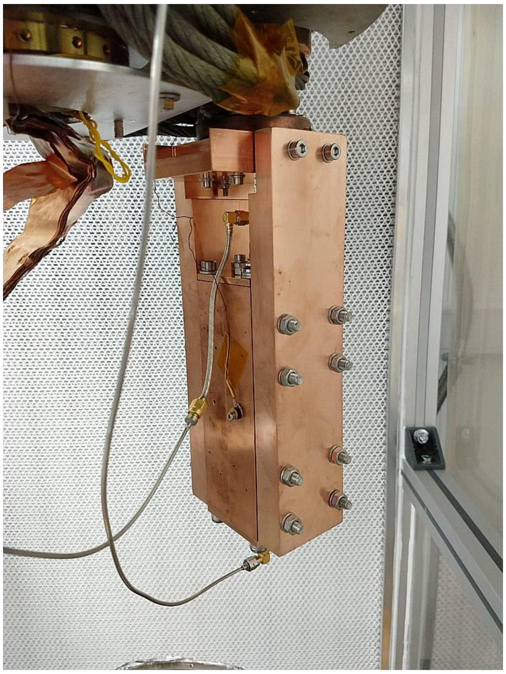

Figure 3: The cavity connected to the cold head before the heat shield and outer vacuum chamber were installed.

Table 1: Surface Resistance Measurements (in Ω) at Each Stage of Cleaning and Polishing

Cavity	As Received	After Clean	at 4.2 K
	Ω		
A	–	2.6×10^{-2}	1.1×10^{-2}
A - polished	2.3×10^{-2}	2.2×10^{-2}	6.3×10^{-3}
B	2.6×10^{-2}	2.4×10^{-2}	6.8×10^{-3}
B - polished	2.2×10^{-2}	2.2×10^{-2}	6.7×10^{-3}
C	2.44×10^{-2}	2.5×10^{-2}	9.5×10^{-3}
C - polished	2.2×10^{-2}	2.5×10^{-2}	4.7×10^{-3}

are 37% higher at RT and 17% higher at 4.2 K, that could be explained by due to the better surface finish of the copper cavities at SLAC.

Superconducting Results

The cavity (‘A’) coated with niobium film was tested at 4.2 K. Heaters attached to the cavity were then used to obtain the surface resistance at higher temperatures. The surface resistance as a function of temperature is reported in Fig. 4.

The critical temperature (T_c) in this section will be quoted as three numbers, T_{c90}, T_{c50} and T_{c10} which are the temperatures corresponding to the surface resistance at 90, 50 and 10% of the superconducting transition, respectively. The coating on the cavity had a $T_{c90} = 8.55 \pm 0.5$ K, $T_{c50} = 8.25 \pm 0.5$ K and a $T_{c10} = 7.6 \pm 0.5$ K. These values are below the expected values for bulk niobium. It could possibly be explained that this is due to some defects in the film.

The surface resistance at 4.2 K was measured to be 5.32×10^{-1} mΩ, the BCS resistance for niobium at 4.2 K at 6 GHz is 1.15×10^{-2} mΩ, which is significantly lower than the measured resistance, this again has been attributed to the defects in the coating.

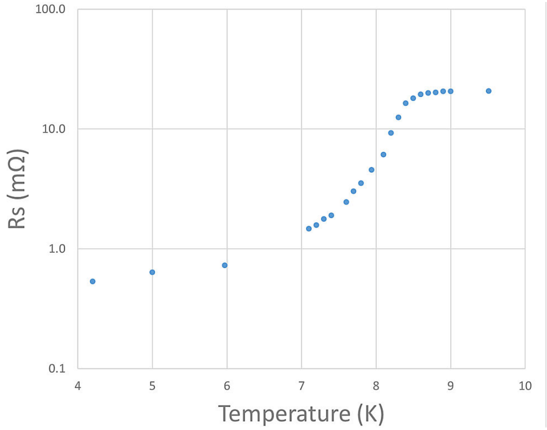

Figure 4: The surface resistance R_s as a function of temperature in the range $4.2\,\mathrm{K} \leq T \leq 9.5\,\mathrm{K}$

Thus, the first split coated split cavity was tested at the temperature range of $4.2\,\mathrm{K} \leq T \leq 9.5\,\mathrm{K}$. This allows to demonstrate that the main idea of split cavity and superconducting thin film coating on it are working, all equipment designed and built for the split cavity testing at cryogenic temperatures is working well.

CONCLUSION

A seamless superconducting thin film radio frequency cavity based on a novel concept of a longitudinal split has been explored by our team. Three OFHC copper cavities were designed, manufactured, mechanically polished and coated with niobium at DL.

One of the advantages of this open geometry design is that the cavities can easily be manufactured, polished, cleaned, coated and examined at every stage.

The Nb coating had a lower T_c than pure Nb and a higher surface resistance, it is expected that this is due to defects within the coating.

Future work will include testing of other coatings and upgrading the system to perform measurements at higher power. A study on the effect of the sharpness of the edges where the two halves of the cavity meet on the performance of the cavity will also be undertaken.

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