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A MULTI-LAYERED SRF CAVITY FOR CONDUCTION COOLING APPLICATIONS*

G. Ciovati†, G. Cheng, E. Daly, G. Eremeev, J. Henry, R. Rimmer, Jefferson Lab, Newport News, VA, USA
U. Pudasaini, The College of William and Mary, Williamsburg, VA, USA
I. Parajuli, Old Dominion University, Norfolk, VA, USA

Abstract

Industrial applications of SRF technology would favor the use of cryocoolers to conductively cool SRF cavities for particle accelerators, operating at or above 4.3 K. In order to achieve a lower surface resistance than Nb at 4.3 K, a superconductor with higher critical temperature should be used, whereas a metal with higher thermal conductivity than Nb should be used to conduct the heat to the cryocoolers. A standard 1.5 GHz bulk Nb single-cell cavity has been coated with a ~2 µm thick layer of Nb_3Sn on the inner surface and with a 5 mm thick Cu layer on the outer surface for conduction cooled applications. The cavity performance has been measured at 4.3 K and 2.0 K in liquid He. The cavity reached a peak surface magnetic field of ~40 mT with a quality factor of 6×10^9 and 3.5×10^9 at 4.3 K, before and after applying the thick Cu layer, respectively.

INTRODUCTION

The progress made over the last few years on the development of Nb_3Sn for superconducting radio-frequency (SRF) accelerator cavities made it attractive for applications in which the cavities operate at a moderate accelerating gradient, E_{acc} ~ 10-15 MV/m, but at 4.3 K, instead of the more typical temperature of 2 K [1].

One such application is for a possible industrial use of SRF accelerators, in which the cavities are cooled by conduction using cryocoolers [2, 3]. Modern crycoolers have a cooling power of up to ~2 W at 4.3 K and either one or multiple of them can be used to cool an SRF cavity in a cost effective manner, compared to using a liquid helium refrigerator.

Since the area of the second stage of a typical cryocooler is only a few square inches, and cooling of the inner cavity surface where the RF power is dissipated can only occur by conduction, it is important to have a layer with high thermal conductivity at ~4 K between the cavity and the cryocooler's second stage.

Currently, the best performing Nb_3Sn films have been obtained by the vapour diffusion method developed at University of Wuppertal in the 1990s [1]. Such method requires heating of a Nb cavity substrate to ~1200 °C, which is higher than the melting temperature of common high-thermal conductivity metals such as copper and aluminium. Therefore, the coating of the outer cavity surface with either copper or aluminium would need to be done after the Nb_3Sn film has been deposited on the inner surface. The outer coating should also be deposited near room temperature conditions, as temperatures above ~100 °C in air might have deleterious effect on the performance of the Nb_3Sn film.

The processes used to fabricate the multi-layered cavity and the cryogenic RF test results are described in this contribution.

Nb_3Sn COATING

A single-cell Nb cavity, labelled SC-IB, made of large-grain Nb from CBMM, Brazil, with residual resistivity ratio of ~280 was used for this study. The cell shape is that of a High-Gradient cavity as was proposed for the CEBAF 12 GeV Upgrade (G = 266 Ω, E_p/E_{acc} = 1.77, B_p/E_{acc} = 4.47 mT/(MV/m)) and the resonant frequency of the accelerating mode is at 1.49 GHz [4]. The cavity wall thickness is ~2.9 mm and the end flanges are made of pure Nb.

The coating of the inner surface with Nb_3Sn was done as follows: SC-IB was placed on top of another single-cell cavity, RDT2, using niobium blanks and molybdenum fasteners. RDT2 was next to the Sn source. A crucible with 6 g of Sn (99.999% purity from Sigma Aldrich) and 3 g of SnCl2 (99.99% purity from Sigma Aldrich), packaged inside two pieces of Nb foils were placed at the bottom flange, covering the beam pipe of RDT2.The top beam pipe of SC-IB was closed with a niobium cover. The coating setup was assembled inside the clean room and then installed onto the furnace insert [5].

Once the insert pressure reached 2×10^{-5} Torr, the furnace was heated by ramping up the temperature at a rate of 6 °C/min until it reached ~ 500 °C. This temperature was then kept constant for one hour and subsequently ramped up at a rate of 12 °C/min up to the coating temperature of ~1200 °C. The temperature was monitored with sheathed type C thermocouples attached to the cavities at different locations. After maintaining the coating temperature for three hours, heating ceased, and the furnace was allowed to cool down gradually. When the furnace temperature reached below 45 °C, the insert was backfilled to 1 atm with nitrogen, and the coated cavities were taken out from the deposition system. Visual inspection from both end of SC-IB indicated a uniform coating as shown in Fig. 1.

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†gciovati@jlab.org

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The cavity was then degreased, high-pressure rinsed with ultrapure water, assembled with stainless steel flanges with pump-out port and RF feedthroughs and sealed to the cavity with In wire. The cavity was evacuated on a vertical test stand, three flux-gate magnetometers were attached at the equator with their axis parallel to the vertical cavity axis. Temperature sensors were also attached at the top and bottom iris and at the equator.

Figure 1: A picture of SC-IB interior after Nb_3Sn coating.

The cavity was inserted in a vertical cryostat at Jefferson Lab's Vertical Test Area and cooled to 4.3 K with liquid helium. The resonant frequency was tracked with a vector network analyzer during cool-down and the critical temperature was T_c ~ 17.8 K. The cavity was slow-cooled through T_c, resulting in a temperature gradient of ~100 mK between top and bottom iris.

The cavity was tested at 4.3 K and at 2 K and a plot of the quality factor, Q_0, as a function of the peak surface magnetic field, B_p, is shown in Fig. 2. The cavity was limited at 4.3 K starting at B_p ~ 40 mT and by quench at B_p ~ 66 mT at 2 K. No field emission was detected during the test.

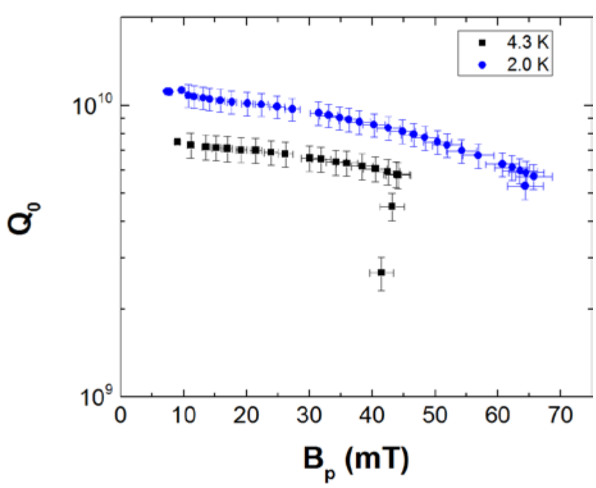

Figure 2: $Q_0(B_p)$ measured at 4.3 K and 2.0 K after the first Nb_3Sn coating[1]. The cavity was limited by anomalous heating at 4.3 K and by quench at 2.0 K.

[1] RF losses on the stainless steel flanges are estimated to be 14.3 mW/mT^2 per flange and have been subtracted from the measured Q_0.

The inner surface of the cavity was etched by buffered chemical polishing (BCP) with $HF:HNO_3:H_3PO_4$ = 1:1:2 by volume, removing ~15 µm. In order to evaluate the reproducibility of the process, the Nb_3Sn coating process was repeated in the same way as the first coating except the positions of SC-IB and RDT2 were interchanged. Visual inspection of SC-IB showed uniform coating, but a few shiny spots were present on the surface, as shown for example in Fig. 3.

The cavity was then prepared as mentioned above for the cryogenic RF test and cooled-down to 4.3 K following the same process mentioned above for the first test. The test results are shown in Fig. 4. The cavity was limited by a quench at B_p ~ 52 mT at 2 K. The quality factor decreased by only ~5% after quenching.

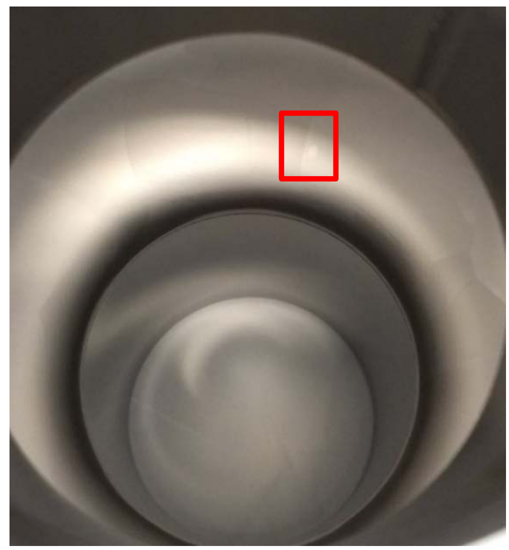

Figure 3: A picture of SC-IB interior after second Nb_3Sn coating. Note the shiny spot marked by red rectangle.

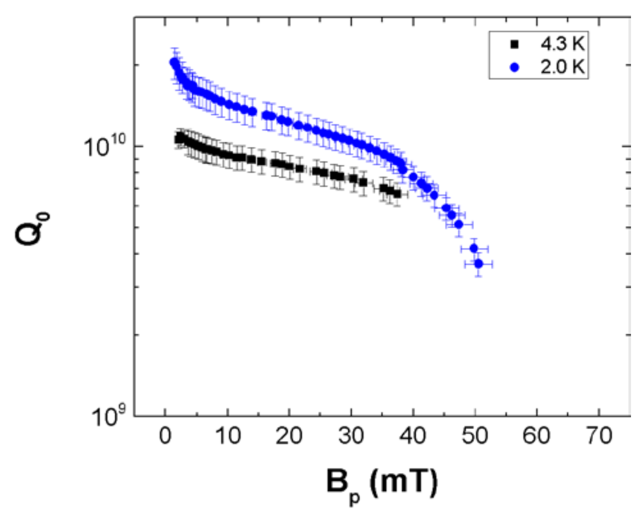

Figure 4: $Q_0(B_p)$ measured at 4.3 K and 2.0 K after the second Nb_3Sn coating[1]. The cavity was limited by quench at 2.0 K.

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COPPER COATING

Samples Measurements

Electroplating is a possible low-cost method to deposit copper on the outer cavity surface at room temperature. However, it should be verified that both good adhesion and high thermal conductivity of the electroplated copper onto the Nb substrate can be achieved.

Six Nb samples, 3.175 × 3 mm^2 cross-section, 75 mm long and two Nb samples, 25 mm wide, 1 mm thick, 140 mm long were cut by wire electro-discharge machining (EDM) from a high-purity, fine-grain (ASTM > 5) Nb sheet used for SRF cavity fabrication. The samples were chemically etched by BCP to remove ~100 µm from the surface, annealed in a vacuum furnace at 600 °C/10 h, followed by BCP removing ~25 µm. The samples were Cu-plated at A. J. Tuck Co. to deposit 3 mm thick copper on one side. The surface to be plated was sand-blasted with coarse grit on three of the samples, labelled No. 1-3.

The thermal conductivity, κ, of one Nb sample and of four Nb/Cu samples was measured as a function of temperature, between 1.5 K – 6.5 K, along the samples and the data are shown in Fig. 5. Samples 4 and 5 had poor adhesion of the Cu on the Nb and this correlates with the lower thermal conductivity. The thin, wide Nb strips were used to try developing a process with improved, reliable adhesion of the Cu on the Nb. Different processes were tried without success.

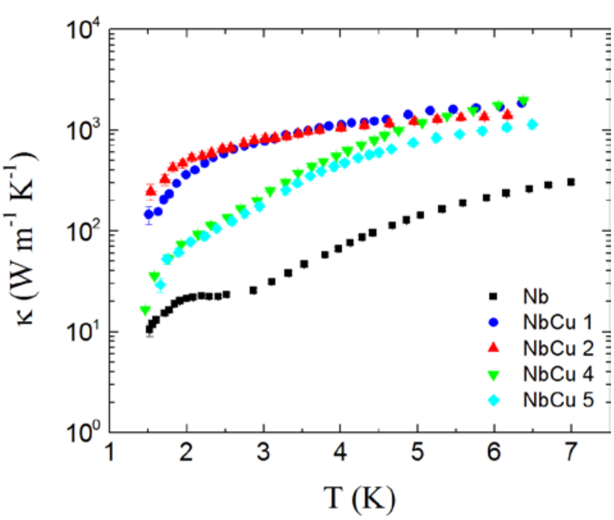

Figure 5: Thermal conductivity as a function of temperature measured on a Nb strip and on four Nb/Cu strips.

Cavity Coating and Test Results

The samples study showed that κ(4.3 K) ~ 1 kW/(m K) could be achieved with electroplated copper onto Nb but without reliable strong bonding at the Nb/Cu interface. Cold-spray is a relatively new technique that allows spraying a metal powder on a substrate at very high speed. As the metal particles hit the surface, they undergo a plastic deformation and bond to the surface. Since the purity of the Cu powder is not as good as that of electroplated copper, cold-spray was considered as a method to create a "seed" layer onto the Nb surface, onto which one can build up the thick Cu layer by electroplating.

Nb samples of the same size as those prepared for the plating study were cold-sprayed with Cu at Concurrent Technologies Corporation (CTC). The thin strips were then plated with 1 mm thick Cu at A. J. Tuck Co. and good adhesion was verified by a bend test.

The single-cell SC-IB was cold-sprayed with Cu powder of purity 99.9% and ~40 µm particle size at CTC. Helium was used as the gas carrier and the distance between the cavity surface and the spray gun was kept at ~1.3 cm using a robotic controlled arm. The cavity rotated at 0.8 rev/sec during the coating process and the coating thickness was ~76 µm, as determined by a micrometer measurement on the flat samples, coated with the same parameters as the cavity. A picture of the cavity after cold-spray is shown in Fig. 6. The cavity was sealed with stainless flanges and Gore-Tex gaskets during the cold-spray.

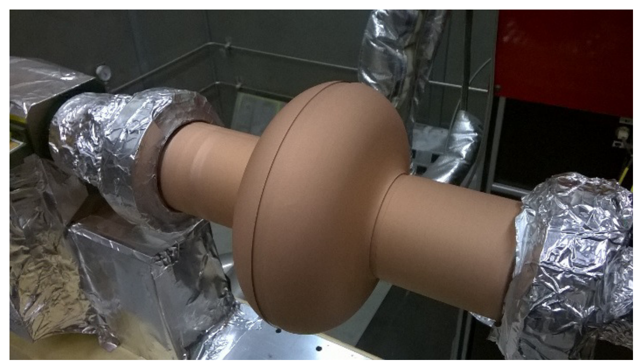

Figure 6: Single-cell cavity after deposition of a thin layer of copper on the outer surface by cold-spray.

The next step was to deposit the thick copper layer by electroplating. The thickness of the layer was determined to be 5 mm from a finite element thermal analysis with ANSYS®, considering the RF losses at the maximum field at 4.3 K shown in Fig. 4 and cooling with a single cryocooler. A ring ~25 cm in diameter and ~1.3 cm thick had to be grown at the equator as well, in order to provide a large contacting surface for the thermal link between the cavity and the cryocooler.

The plating was done in multiple steps, with intermediate masking to allow growing the minimum thickness in regions of low current density, such as the irises, and of the thick center ring. Sanding of lumps was done as well between plating cycles. It took 90 days of plating to grow the whole layer.

At the end of the plating process, it was found that some of the $CuSO_4$ solution had leaked into the cavity. Inspection of the inner surface with a boroscope showed one ~1 mm size Cu particle on the surface. Such particle was removed by degreasing the cavity. As a precaution, the cavity was filled with HNO_3(35%) at room temperature for 1 h to dissolve any possible $CuSO_4$ residue.

Afterwards, the cavity was machined on a lathe to remove the excess copper. Flood cooling was used and the

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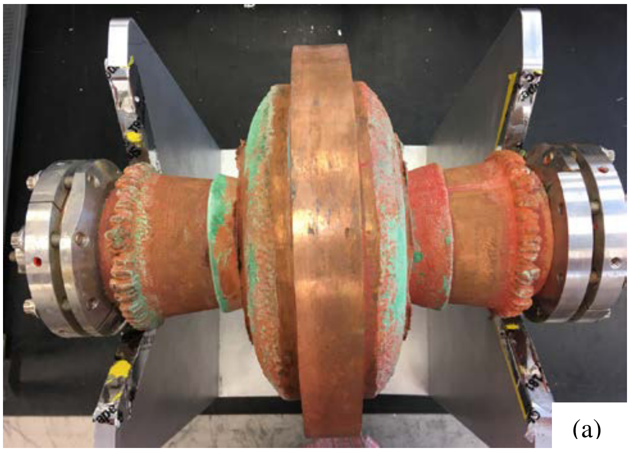
peak temperature during machining did not exceed 35 °C. Pictures of the cavity after plating and after machining are shown in Fig. 7.



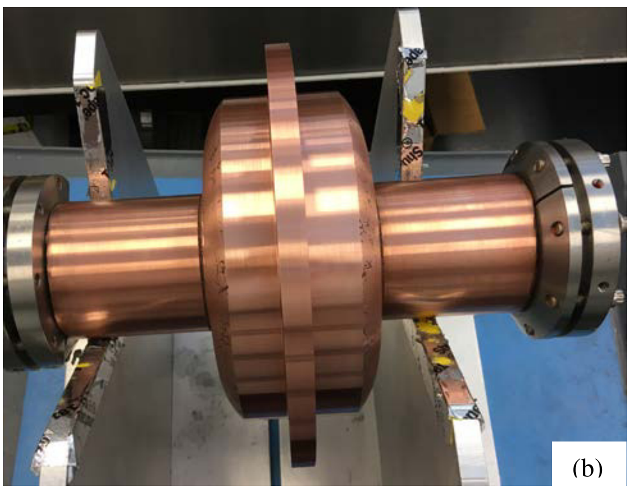


Figure 7: Single-cell cavity after Cu-plating (a) and machining (b).

The cavity was then degreased, high-pressure rinsed with ultra-pure water, dried in an ISO 5 clean room, assembled with a variable input coupler [6], a pump-out port and a pick-up probe. The cavity was evacuated on the vertical test stand. Cernox temperature sensors were attached at the iris and equator. The cavity was cooled from 295 K to ~20 K at a rate of ~10 K/min, whereas cooling was slowed at ~18 K to achieve a temperature difference of ~100 mK between the top and bottom irises. The cryostat was then filled with liquid He at 4.3 K followed by pumping on the He bath until achieving 2.0 K.

The frequency shift from 295 K, 1 atm, to 4.3 K, ultra-high-vacuum, increased from ~2.4 MHz to ~6.3 MHz after the Cu layer was added. This is due to the larger thermal contraction of Cu compared to that of Nb. The pressure sensitivity decreased from ~180 Hz/Torr to ~27 Hz/Torr because of the thicker walls after the Cu layer was added.

The results from the cryogenic RF tests of the multi-layered cavity at 4.3 K and 2.0 K are shown in Fig. 8. The cavity was limited at 4.3 K by "Q-switches" at ~36 mT, whereas it quenched at ~54 mT at 2.0 K. The Q_0 at 2 K decreased by ~40% after ~10 quenches. No field emission was detected. The power dissipated in the cavity at 4.3 K is ~1.5 W at B_p = 34 mT, just before the occurrence of the Q-switch. The resonant frequency was tracked during warm-up and T_c was found to be ~17.8 K.

The data in Fig. 8 show that the performance degraded after the addition of the copper layer, above ~15 mT. One possible reasons is strain in the Nb_3Sn film resulting from the differential thermal contraction between Nb and Cu. It is well known that the superconducting properties of Nb_3Sn are very sensitive to strain [7]. A finite element analysis with ANSYS® shows that stresses as high as ~275 MPa at the irises and ~185 MPa elsewhere on the cell may be applied to the Nb_3Sn-coated Nb, due to the larger thermal contraction of Cu.

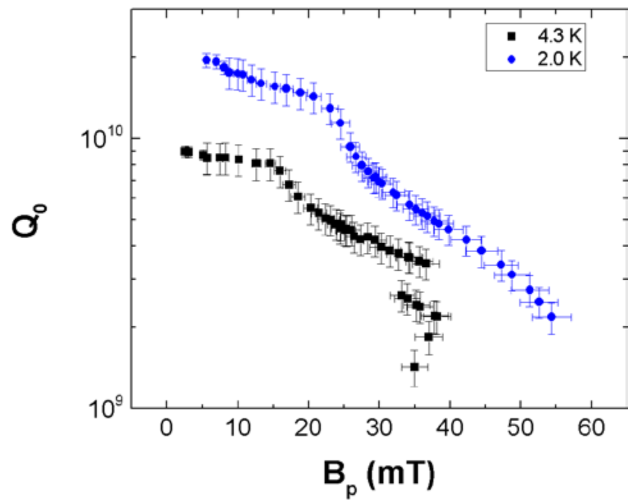


Figure 8: $Q_0(B_p)$ measured at 4.3 K and 2.0 K after depositing a ~5 mm thick Cu layer on the cavity outer surface[1]. The cavity was limited by quench at 2.0 K.

CONCLUSION

A multi-layered cavity with a thin Nb3Sn coating formed on the inner surface of a Nb cavity and a thick Cu coating on the outer surface was built and tested at 4.3 K and 2.0 K. The cavity reached ~40 mT at 4.3 K and ~50 mT at 2.0 K. The Q_0 degraded at high-field after applying the thick Cu layer, possibly due to strain of the film resulting from the differential thermal contraction between Cu and Nb.

The cavity will be attached to a test setup with a cryocooler to measure its performance using conduction cooling instead of a liquid helium bath.

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