FIRST RESULTS FROM TWO Nb_3Sn CAVITIES ASSEMBLED IN A CEBAF QUARTER CRYOMODULE

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ABSTRACT

Two 1.5 GHz CEBAF C75-shape 5-cell accelerator cavities were coated with Nb_3Sn film using the vapor diffusion technique at Fermilab and Jefferson Lab coating facilities. Both cavities were measured at 4 K and 2 K in the vertical cavity test facility (VCTF) in each lab, then assembled into a CEBAF quarter cryomodule at Jefferson Lab. The cryomodule was tested at 4 K and 2 K in the CryoModule Test Facility (CMTF) at Jefferson Lab. RF test results for both cavities in the cryomodule are similar to those in the qualification test in VTS, with one cavity reaching Eacc = 7.9 MV/m and the other - 13.3 MV/m at 4 K.

INTRODUCTION

Nb_3Sn superconducting material is a promising superconductor for accelerator cavities, which has been shown to sustain magnetic fields close to 100 mT, corresponding to accelerating gradients of about 20 MV/m [1–5]. There are several cryomodule development projects underway that aim to exploit this superconducting RF technology for accelerator applications [6–12]. Present contribution discusses the challenges and progress to qualify and install two C75 cavities [13] coated with Nb_3Sn into a spare CEBAF quarter cryomodule. The goal for this cryomodule is to be installed in the Upgraded Injector Test Facility (UITF) at Jefferson Lab and to have its operation tested with the beam as well as to provide the electron beam to UITF experiments [14].

CAVITY QUALIFICATION

Two niobium 5-cell cavities, built RI Research Instruments, GmbH, according to Jefferson Lab C75 specifications [13], were coated with Nb_3Sn coating. 5C75-RI-NbSn1 cavity was made from the fine grain material, and 5C75-RI-004 cavity cells were made from the large grain material. The cavities received the standard processing and were tested to Eacc ≈ 29 MV/m for 5C75-RI-NbSn01 limited by the high field Q-slope, and to Eacc ≈ 19 MV/m for 5C75-RI-04 limited by multipacting-induced quench.

After Nb_3Sn coating, 5C75-RI-004 was found to be uniformly coated with a matte appearance typical for the developed multi-cell cavity coating protocol [15].

A slow cooldown protocol was implemented during the vertical test to cool the cavity uniformly. The temperature gradient across the cavity was maintained at about 100 mK while cooling down through the superconducting transition temperature. RF test results at 4 K are shown in Figure 1. The cavity quality factor was about $2{\cdot}10^{10}$ at the low fields and was above $1{\cdot}10^{10}$ at $E_{acc} \approx 10$ MV/m at 4 K. The quality factor was measured up to $E_{acc} \approx 13.3$ MV/m before a multipacting barrier was encountered and the test was stopped. The low-field quality factor was above $3{\cdot}10^{10}$ at 2 K. The quality factor exhibited a field dependence similar to that in 4 K test, but with a high quality factor.

The 5C75-RI-NbSn01 cavity received 35 um of electropolishing in the Argonne National Laboratory facility to reset the Nb_3Sn-coated surface for the new coating. The complete cavity was then anodized at 30 V in a 0.1 M diluted sulfuric acid solution as a part of the coating protocol followed in Fermilab. The anodized cavity was coated following the coating protocols developed for multi-cell Nb_3Sn coating at Fermilab [16]. This was the first time a C75-shaped five-cell cavity was processed and coated at these facilities.

The cavity was visually observed to be uniformly coated and glossy, similar to several other cavities coated at Fermilab. The coated surface appeared shinier than the one at Jefferson Lab, likely due to the thinner coating.

RF test was done at 4.4 K and 2 K after a slow cooldown. The cavity's quality factor was above $1{\cdot}10^{10}$ at low fields and was close to $1{\cdot}10^{10}$ at $E_{acc} \approx 10$ MV/m at 4 K. The maximum gradient was limited to $E_{acc} \approx 14$ MV/m by multipacting-induced quench. The quality factor was about $6{\cdot}10^{9}$ at the maximum field. The low-field quality factor was above $4{\cdot}10^{10}$ at 2 K. The quality factor exhibited a field dependence similar to that in the 4 K test, but with a high quality factor.

Since both cavities met the gradient targeted for the quarter cryomodule to be installed in the UITF, they were progressed to the pair assembly. After the pair assembly, a warm leak was detected in the ceramic window attached to the fundamental power coupler of the 5C75-RI-04 cavity. Since the pair needed to be re-assembled, each cavity was re-tested individually in VCTF.

Following the disassembly from the pair, each cavity followed the typical processing steps for RF testing. It was discovered that the 5C75-RI-04 cavity performance was degraded compared to the test before the pair assembly. The low field quality factor dropped to about $1{\cdot}10^{10}$ at low fields at 4 K, and a sharp Q-drop was observed starting at $E_{acc} \approx 3$ MV/m. The cavity was limited to $E_{acc} \approx 8$ MV/m, as shown in Figure 1. 5C75-RI-NbSn01, on the other hand, did not show any noticeable degradation. The cavity reached $E_{acc} \approx 20$ MV/m at 2 K after multipacting processing.

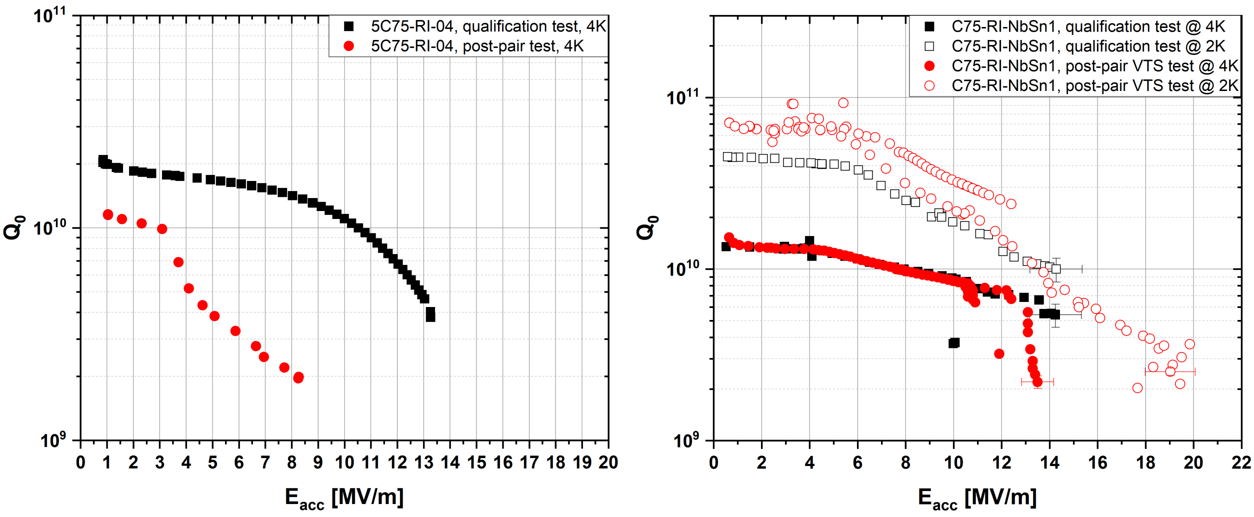

Figure 1: *Vertical test qualification results for 5C75-RI-004 and 5C75-RI-NbSn01 after Nb_3Sn coating. [left plot]4K 5C75-RI-004 test results before the pair assembly(black squares) and after the cavity was disassembled from the pair(red circles). Note performance degradation after the pair assembly;[right plot]4K and 2K 5C75-RI-NbSn1 test results before the pair assembly(black squares) and after the pair assembly (red circles). Note no performance degradation after the pair assembly.*

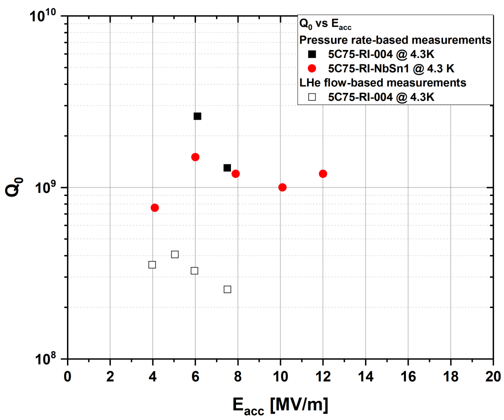

Figure 2: *Cryomodule test results at 4 K. Solid symbols were measured using the pressure rate of rise technique. Empty symbols were measured using the liquid helium flow technique. Note the spread between the measurements for 5C75-RI-04 cavity.*

After the cavities were re-qualified, they were assembled again into a pair. The assembly was evacuated, leak checked, and found to be leak tight. The pair was then rolled out and staged for cryomodule assembly outside the cleanroom.

CRYOMODULE ASSEMBLY

Cryomodule assembly followed the standard assembly process for C75 cryomodules [17] with a few changes: two Cernox^{TM} thermometers were installed on the ends of the cavity pair; two fluxgates were added to each cavity; frequency limit switches were set to allow for a larger frequency tuning range; resonant frequencies of both cavities were recorded after each assembly step; FPC waveguide connection procedure was modified to reduce stresses on the pair; tuner cell holders were left loose, and there was no tuner pre-loading; and the pressure test procedure was modified.

Due to the high sensitivity of coating to mechanical deformation at room temperature, frequencies of both cavities were tracked through the cryomodule assembly process from when the cavity pair was moved out of the cleanroom to the time the cryomodule was moved into CMTF. After the cryomodule assembly, the frequency of 5C75-RI-NbSn1 shifted by about 170 kHz down, while the frequency of 5C75-RI-004 shifted by 20 kHz up. The largest frequency shift was observed after helium vessel welding.

CRYOMODULE TESTING

For the cryomodule test, a set of acceptance criteria was developed to guide the test flow. Based on the acceptance criteria parameters, a separate traveler document was developed for the cryomodule cooldown and testing. One of the critical parameters for the cryomodule cooldown was the temperature difference between the ends of the pair as the cavities cross the superconducting transition temperature of Nb_3Sn. Several cooldowns were done to achieve the temperature difference between two Cernox temperature sensors of 0.3 K. The other concern for the cooldown was that tuner engagement during cooldown may stress the cavities. To mitigate this concern, frequencies of the cavities were tracked and compared against the expected frequencies vs temperature. The cooldown was also stopped at several points and tuners were exercised to confirm that they did not engage the cavities.

Since accelerator cavities in cryomodule are loaded by the power coupler, the standard vertical test techniques do not

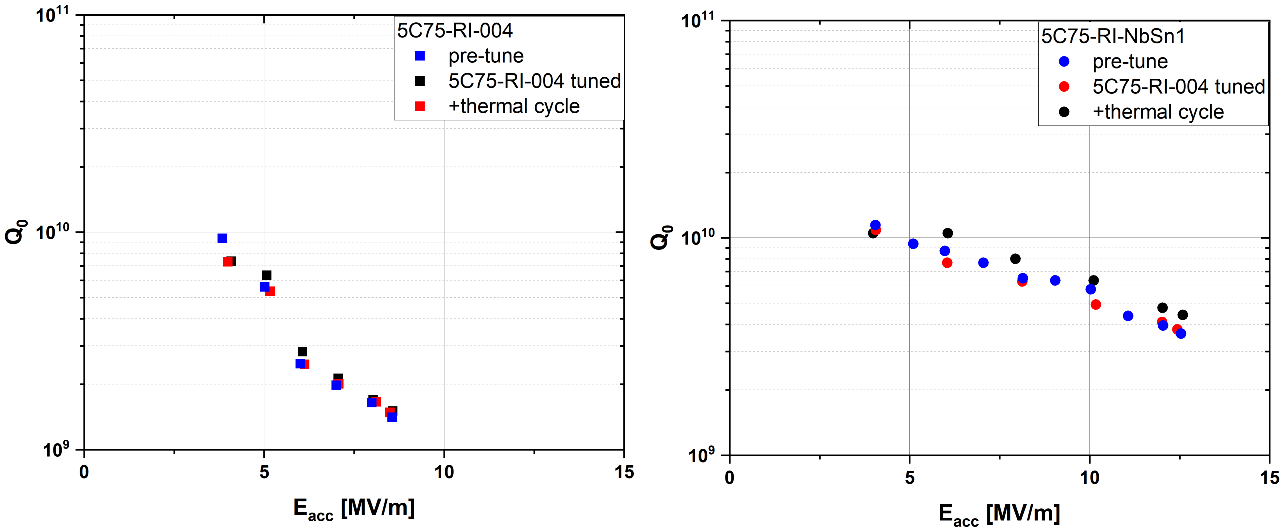

Figure 3: *Cryomodule test results at 2 K for three different cooldowns. [left plot] 5C75-RI-004 test results. Note no performance degradation after this cavity was tuned to the resonant frequency of 5C75-RI-NbSn01; [right plot] 5C75-RI-NbSn01 test results. Note that the quality factor field dependencies are similar to those observed in the last vertical test, Fig.* 1

accurately measure the intrinsic quality factor of the cavities. Two techniques are typically used to measure the intrinsic quality factors of accelerator cavities at 2 K at JLab. One technique measures the rate of the helium pressure rise, and the other measures the liquid helium flow to the cryomodule. These techniques were tried for the first time to measure Nb_3Sn cavities at 4 K. Quality factor measurements, using the rate of rise technique, are shown at 4 K in Fig. 2.

While the quality factor measurement cannot be accurately deduced from power balance equations due to instrumental accuracy, the accelerating gradient measurement relates to the total stored energy in the cavity, which can be accurately calculated from the power emitted by the cavity. The results in Fig. 2 show that one of the cavities reached E_{acc} = 7.9 MV/m, while the other cavity reached E_{acc} = 13.3 MV/m at 4 K. The one hour run at 4 K was done at E_{acc} = 7.5 MV/m for 5C75-RI-04 and at E_{acc} = 12.5 MV/m, which were established as operating gradients for these cavities.

After the first cooldown, the gradient and field emission of each cavity were measured at 4 K. The cryomodule was then warmed to about 30 K and cooled down to 2 K, where the quality factors were measured. After these measurements, 5C75-RI-004 was tuned to the frequency of 5C75-RI-NbSn01. The cryomodule was then warmed up to about 30 K and cooled down again to 2 K, where the final 2 K measurements were done.

In Fig 3, the results of quality factor measurements at 2 K are shown. The difference in the quality factors between different cooldowns was within the experimental error. Notably, tuning one of the cavities in the cryomodule did not degrade its performance, consistent with the previously reported result from a single-cell cavity tuned at a similar temperature in the vertical dewar test [16].

CONCLUSION

CEBAF quarter cryomodule was assembled with two 1.5 GHz CEBAF C75-shaped 5-cell accelerator cavities, which were coated with Nb_3Sn film using the vapor diffusion technique. The cryomodule was tested at 4 K and 2 K in CMTF at Jefferson Lab. RF test results for both cavities in the cryomodule were similar to the results in the last qualification test in VCTF. One cavity reached E_{acc} = 7.9 MV/m and the other - 13.3 MV/m at 4 K, resulting in more than 10 MV voltage gain for this cryomodule.

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