ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV001

CAVITY PRODUCTION AND TESTING OF THE FIRST C75 CRYOMODULE FOR CEBAF*

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Abstract

The CEBAF cryomodule rework program was updated over the last few years to increase the energy gain of refurbished cryomodules to 75 MeV. The concept recycles the waveguide end-groups from original CEBAF cavities fabricated in the 1990s and replaces the five elliptical cells in each with a new optimized cell shape fabricated from large-grain, ingot Nb material. Eight cavities were fabricated at Research Instruments, Germany, and two cavities were built at Jefferson Lab. Each cavity was processed by electropolishing and tested at 2.07 K. The best eight cavities were assembled into "cavity pairs" and re-tested at 2.07 K, before assembly into the cryomodule. All but one cavity in the cryomodule were within 10% of the target accelerating gradient of 19 MV/m with a quality factor of 8×10^9. The performance limitations were field emission and multipacting.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab has forty 8-cavity cryomodules (CMs) originally built in the 1990s [1]. Field emission is the main limitation for the operation of the cryomodules and results in a steady beam energy loss over time [2]. A refurbishment program was started in 2006 to remove the lowest-performing CMs from the accelerator, at a rate of about one CM per year, and reprocess the cavities to increase the energy of the CM to 50 MeV, from the original ~20 MeV [3]. The rework program was updated in 2016 to further increase the energy of the CMs to 75 MeV, at the lowest possible cost. The proposed concept was to reuse the waveguide end-groups of the old cavities and replace the 5-cells with new ones with a more efficient shape and with low-cost large-grain, ingot Nb [4]. Three prototypes of such "C75" cavities were built, processed and tested at Jefferson Lab in 2016 and two of them were installed in the last C50 CM, which has been operating in CEBAF since December 2017 [5]. The current plan requires nine C75 reworked CMs to be installed in CEBAF over the next 5 years.

CAVITY FABRICATION, TREATMENT AND VERTICAL TEST RESULTS

Two C75 cavities, 5C75-J-004 and -005 were fabricated at Jefferson Lab in 2018 and eight cavities, 5C75-RI-001 to -008 were built at Research Instruments (RI), Germany in 2018-19. The Nb material used for the elliptical cells was obtained from ingots from CBMM, Brazil, sliced into 3.155 mm thick discs by multi-wire slicing at Slicing Tech, USA. The ingots' Ta content was 923 wt.ppm and 139 wt.ppm for the cavities built at JLab and RI, respectively. The RRR measured on samples cut from the discs was 165 and 203 for the material used at JLab and RI, respectively. The cost of the Nb discs was ~1/3 of the cost that was quoted for the conventional fine-grain, high-RRR, low-Ta Nb disc.

The cavity fabrication followed conventional methods such as deep-drawing of the Nb discs and electron-beam welding of parts. A re-shaping tool was used at the dumbbell stage, both at JLab and RI, to correct the shape. The cavities were received tuned and with >95% field flatness from RI. One of the cells of cavity 5C75-RI-008 had a narrow underbead at one of the equator welds, the joint was missed at two locations and had to be sent back to RI for a partial re-weld. Figure 1 shows a picture of a C75 cavity built at RI.

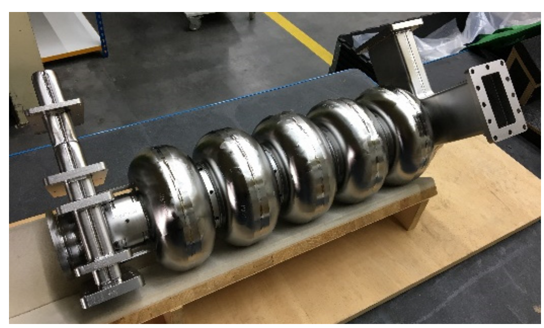

Figure 1: Picture of a C75 cavity built at RI.

All of the surface treatments were done at JLab and can be summarized as:

- 100 ↘m removal by electropolishing (EP)
- Vacuum annealing at 800 °C/3 h
- 30 ↘m removal by EP
- Dimensional check/adjustment and RF tuning
- Lapping and buffered chemical polishing of Nb flanges
- High-pressure rinse with ultra-pure water
- Assembly of ancillary components in an ISO Class 4 cleanroom
- Slow evacuation on a vertical test stand and leak check.

The amount of material removal was calculated from the total charge during EP and confirmed by measuring the wall thickness at the equator using an ultrasonic probe.

* This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.
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Cryogenic RF Test Results of Single-Cavities

The cavities were tested individually to verify their RF performance at 2.07 K, with a goal of $Q_0 = 8\times10^9$ at E_{acc} = 20.5 MV/m. Three fluxgate magnetometers and Cernox temperature sensors were attached at the equator of the top, middle and bottom cell to verify that the residual magnetic field during cool-down was less than 10 mG and six oscillating superleak transducers were mounted on the cavity frame to determine the quench location.

Figure 2 shows the $Q_0(E_{acc})$ data at 2.07 K for all ten cavities. The average residual resistance was (4.5 ± 1.7) n␣. Surprisingly, the main performance limitation was multipacting (MP). A "soft" barrier was found between 13 – 15 MV/m, except for cavity 5C75-RI-008 for which the MP barrier was "hard" and did not process. As the MP caused a breakdown of the cavity field, often without any X-rays, it was not always obvious to clearly distinguish between MP and thermal quench above 18 MV/m. Two cavities (5C75-RI-005 and 5C75-RI-007) reached ~25 MV/m and after a few breakdown events at that gradient, they fell into a MP barrier at ~21.5 MV/m. A similar situation occurred in 5C75-RI-003 upon reaching ~22 MV/m and falling back into a MP barrier at 19 MV/m. Testing of 5C75-RI-002 was administratively limited to 20.8 MV/m. A thermal quench was found at the equator of one of the cells of 5C75-J-005 and two possible geometrical defects were found at the quench location after inspection, although such defects were not significantly different from others inside the cavity.

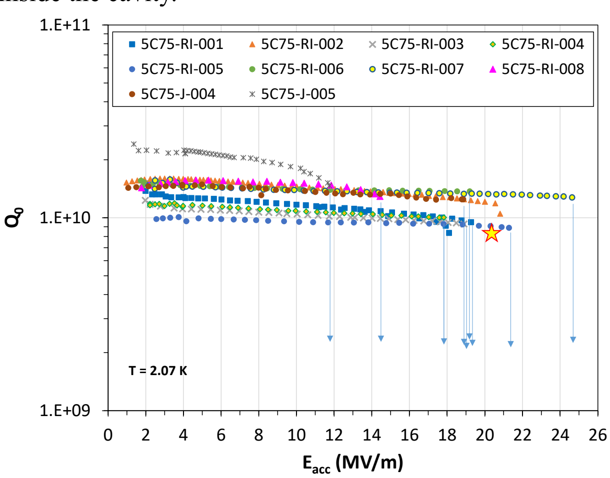

Figure 2: Summary of RF performance of ten C75 cavities tested as single-cavities in a vertical cryostat. The arrows indicate the breakdown field.

Cryogenic RF Test Results of Cavity-Pairs

The original CEBAF CMs are segmented into four "cryounits", each containing a hermetically sealed cavity-pair, installed in a common He vessel [6]. Several components are attached to the two cavities to form a cavity pair, inside the cleanroom: an "inner adapter" connecting the beamline of the two cavities, "elbows", high-order mode (HOM) loads, fundamental power coupler (FPC) "doglegs", "end-dishes" with beamline valves. The end-dishes and the flanges to which the HOM loads are attached are made of stainless steel, the HOM loads are made of a RF-absorbing ceramic material, a rectangular alumina RF vacuum window is brazed into the FPC dogleg. All other components are made of Nb. All the vacuum seals are made using In wire. Each cavity is high-pressure rinsed before assembly into a cavity pair. Figure 3 shows a picture of a C75 cavity pair attached to a vertical test stand. A Nb coax-to-waveguide adapter ("top-hat") with a port for an antenna is bolted to each dogleg to which the input power RF cable can be attached. The field probe port is located on one of the HOM waveguides. The cavity-pair is isolated from the turbo-pump on the vertical test stand prior to cool-down, to allow for the He-desorption leak test [7]. Fluxgate magnetometers and temperature sensors are attached to the top cell of the top cavity, mid-way and at the bottom cell of the bottom cavity to verify that the residual magnetic field was less than 10 mG during cool-down.

Figure 3: C75 cavity pair attached to a vertical test stand.

Figure 4 shows the final results of the 8 cavities built into cavity pairs, tested in a vertical cryostat at 2.07 K. Some of the cavity-pairs required multiple re-built because of issues with vacuum leaks or strong field-emission.

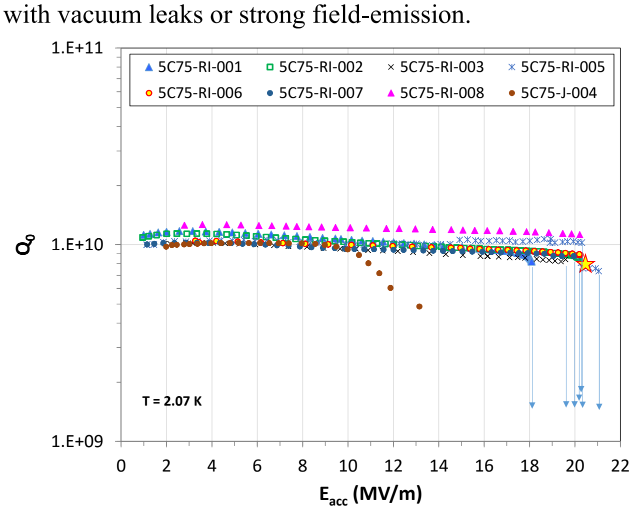

Figure 4: Summary of RF performance of eight C75 cavities built as cavity-pairs each tested in a vertical cryostat. The arrows indicate the breakdown field.

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The maximum gradient, E_{max}, was limited by MP, similarly to the single-cavity tests. The RF performance of cavity 5C75-J-004 was limited by strong field emission, but the schedule did not allow for sufficient time to re-process the cavity. The Q_0-values at low field also degraded by ~19% on average compared to the single-cavity tests and this is understood to be due to RF losses in the metallization of the dogleg ceramic window [8]. The He leak rate values of the four cavity-pairs measured with the He desorption method ranged between (6×10^{-12} – 1×10^{-10}) atm cc/s and were within the specification of $<2\times10^{-10}$ atm cc/s.

CRYOMODULE ASSEMBLY AND TEST RESULTS

Most of the original CM components are re-used for the C75 rework. The major changes are the following:

- The tuner cell-holders are re-machined to match the profile of the new cells
- An inner magnetic shield is added to each cavity, inside the He vessel
- Degaussing of cavity-pair and cold tuner components
- TIG welding during CM assembly was done with grounding close to the welds.
- The FPC waveguide thermal intercept is extended towards the He vessel [9]
- A non-evaporable getter (NEG) pump (Capacitorr HV 200, SAES Getters, Italy) is added to the CM beamline pump section
- The four ion pumps that were used to evacuate pairs of FPC waveguides are replaced with eight NEG and ion combination pumps (NEXTorr D 200-5, SAES Getters, Italy) [10]

Two fluxgate magnetometers (Mag-F probes with Mag01H nanotesla-meter, Bartington Instruments, UK) are attached to each cavity to monitor the residual magnetic field. Si diode temperature sensors are attached to the flange of one of the HOM loads on each cavity, at beamline height. Seven Decarad radiation monitors are placed along the CM vacuum vessel to monitor the dose rate during cavity RF operation. Figure 5 shows a picture of the fully assembled CM installed in the CryoModule Test Facility (CMTF) at JLab.

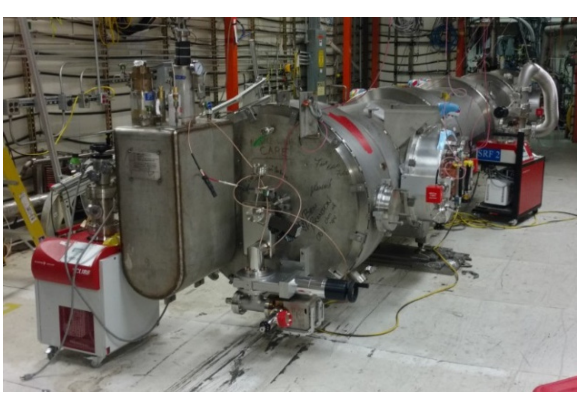

Figure 5: Picture of the CM C75-01 inside the CMTF.

The cavity cooldown rate at 9.2 K was 5 – 14 mK/s and the residual magnetic field at all cavities was less than 10 mG. The design of the He vessel and tuner allows for a very low cavity pressure sensitivity which was measured to be ~27 Hz/Torr on average.

Figure 6 shows the resonant frequency shift as a function of the number of micro-steps of the tuner stepper motor for some of the cavities, at 2 K. A tuning range of up to ~900 kHz was reached.

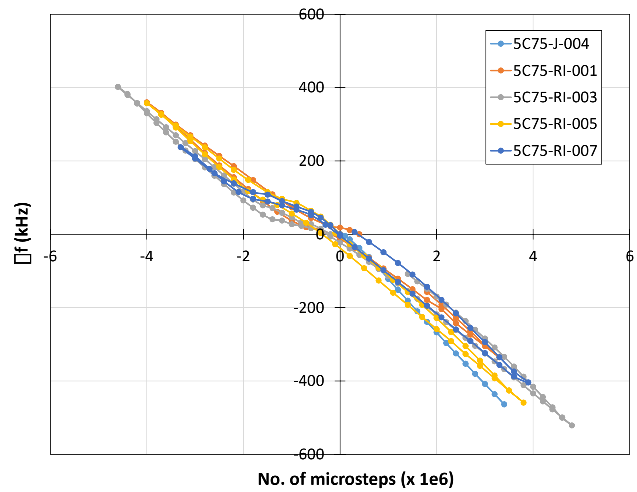

Figure 6: Results from cold tuner range measured in cryomodule C75-01.

The average Q_{ext} of the FPC at 2 K was measured to be $(1.7 \pm 0.3)\times10^6$, lower than the target value of $(2.0 \pm 0.3)\times10^6$. The average Lorentz force detuning of the cavities in the CM was –2.6 Hz/[(MV/m)^2], compared to ↖3.9 Hz/[(MV/m)^2 measured in the vertical cryostat. Figure 7 shows the $Q_0(E_{acc})$ data measured for the cavities in the CM, scaled to 2.07 K, up to the "operational accelerating gradient", E_{op}, which is the highest E_{acc}-value that the cavity can stably operate for at least 1 h. The target operation gradient for 75 MeV energy gain is 19 MV/m. The Q_0-measurements were done with the pressure rate-of-rise method [11]. The static heat load at 2.07 K was (11.5 ± 0.5) W. Table 1 lists some of the key cavities' performance parameters measured in the CM and as cavity-pairs in a vertical cryostat. MP was observed in all cavities in the CM between 13 – 14 MV/m but could be processed.

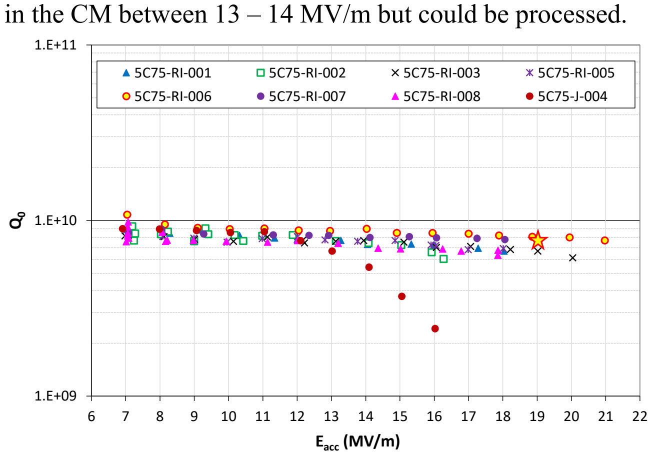

Figure 7: $Q_0(E_{acc})$ scaled to 2.07 K for the C75 cavities measured in CM C75-01 up to the E_{op}-value for each cavity.

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Table 1: Key Performance Parameters of C75 Cavities for the First C75 Cryomodule

Cavity	Vertical test		Cryomodule test		
	E_{max} (MV/m)	Field emission onset (MV/m)	E_{max} (MV/m)	E_{op} (MV/m)	Field emission onset (MV/m)
5C75-RI-008	20.2	N/A	18.4	18.0	N/A
5C75-J-004	13.2	6.9	16.6	16.1	8.2
5C75-RI-001	19.3	14.5	18.5	18.1	13.2
5C75-RI-003	19.6	15.0	21.0	21.0	13.0
5C75-RI-002	20.2	18.2	17.8	17.2	11.1
5C75-RI-005	21.1	19.7	18.3	17.7	N/A
5C75-RI-007	19.9	N/A	18.7	18.1	N/A
5C75-RI-006	20.2	17.5	21.1	20.6	16.3

Similar to the tests in the vertical cryostat, it was not distinguishable whether the breakdown field of the cavities in the CM was caused by MP or by a thermal quench, above ~17 MV/m. For example, E_{max} of 5C75-RI-002 decreased from 20.2 MV/m in the vertical test to 17.2 MV/m in the CM, whereas E_{max} of 5C75-RI-003 increased from 19.6 MV/m in the vertical cryostat to an administrative limit of 21 MV/m in the CM. Three cavities had no detectable radiation dose rate up to E_{max}, whereas the average field emission (FE) onset of the other five cavities decreased from 14.4 MV/m in the vertical test to 12.4 MV/m in the CM. 5C75-J-004 had the strongest field emission, with a maximum dose rate of >10 R/h at 16 MV/m. Figure 8 shows the dose rate as a function of E_{acc} for cavities 5C75-RI-002 and 5C75-RI-003.

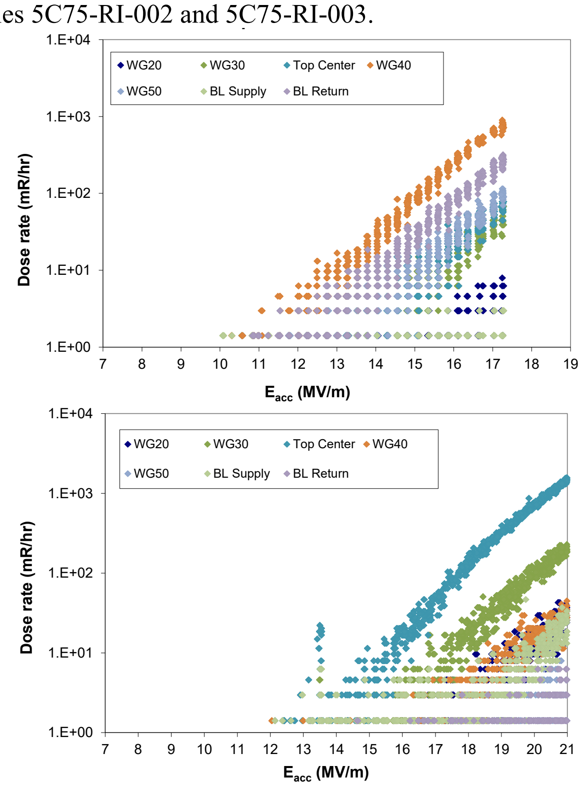

Figure 8: X-rays dose rate as a function of E_{acc} for cavities 5C75-RI-002 (top) and 5C75-RI-003 (bottom) measured at different locations of the CM C75-01.

DISCUSSION

The assembly of cavity-pairs involves many large components requiring 64 indium seals for each cryomodule, directly immersed in superfluid He. This poses a significant challenge towards reproducibly achieving accelerating gradients of the order of 20 MV/m without field emission, compared to “modern” cavity string assemblies. Depending on the dose-rate limit, CM C75-01 could deliver a beam energy from 57 MeV, if all cavities would operate below their FE onset, to 72 MeV, if all cavities would operate at their E_{op}-value. The experience with the C100 CMs, operating in CEBAF at similar accelerating gradient as expected for C75 CMs, suggests that FE maybe the main operational limitation of C75 CMs as well [12, 13]. The energy gain provided by the CMs will likely result from a balance between pushing the CEBAF energy to 12 GeV, with some margin, and limit the radiation dose rate in the tunnel to avoid premature failure of components.

The occurrence of strong MP in the range 17 – 24 MV/m, close to the cavity operational gradient, was unexpected. MP simulations were done using the 2D code FishPact [14] for both end-cell and center-cell shapes, with and without the equator weld-prep geometry. Figure 9 shows the electron’s final kinetic energy after 20 impacts being greater than ~25 eV in the range 23 – 29 MV/m. Given the assumption made for the emission energy in FishPact, this range of impact energies within cavity cells should rather result in a soft MP barrier when compared to the testing experience for other cavities. Apart from the surface cleanliness, it is conceived that the actual details of the weld seam can elevate the impact energies of secondaries to result in a harder MP barrier.

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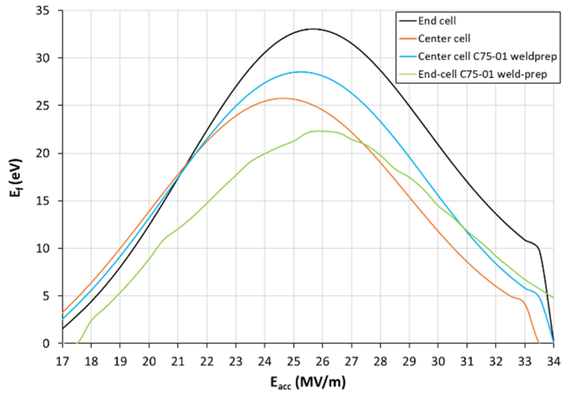

Figure 9: Result of 2D MP simulations for the C75 cavity cell shape.

Further simulations are being carried out with the 3D code ACE3P [15] to better understand the problem.

The Q_0-values of the cavities in C75-01 were the highest ever achieved in original CEBAF CMs, where cavities typically reached Q_0~5×10^9, a factor of two lower than measured in a vertical cryostat [12]. One contribution to the additional losses was from the high remanent field near the cavity [16] but recent detailed RF simulations showed that RF losses in the metallization of the FPC cold window are a major contributor. Such losses are reduced in C75 cavities by design, compared to original CEBAF cavities because of the higher Q_{ext}-specification that required an increased distance between the cavity end-cell and the FPC waveguide [8].

CONCLUSION

Cavities for the first cryomodule for the C75 rework program of CEBAF were manufactured from medium-purity large-grain Nb by RI, Germany, and were processed, tested and assembled into CM C75-01 at Jefferson Lab. Field emission is the main limitation for the beam energy that the CM is expected to deliver in CEBAF. Strong MP was observed in nearly all cavities at fields below what was predicted by 2D MP simulations. The Q_0-values were the highest ever achieved in original CEBAF CMs. The CM has been installed in the CEBAF tunnel and will be retested in August 2021, before the restart of CEBAF operations, and will include measurements of microphonics and HOM spectra. Cavities for the second CM have been received from RI and are currently being processed at JLab.

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