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COMMISSIONING OF THE SECOND JLab C75 CRYOMODULE & PERFORMANCE EVALUATION OF INSTALLED C75 CAVITIES*

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Abstract

JLab has long been a hub of SRF technology with the CEBAF accelerator as one of its first large scale adopters. As SRF technology has advanced, the C50 and C100 programs have allowed for the extension of CEBAF's total energy to 6 GeV and nearly 12 GeV respectively. Along with the increase in energy reach, rates of accelerating gradient degradation have been extracted for these cryomodule designs. A plan to mitigate these losses & maintain robust gradient headroom to deliver the 12 GeV program - the CEBAF Performance Plan - established a multi-year effort of cryomodule refurbishments and replacements. Part of this plan included a cost optimization of the C50 program with more modern processing techniques and the replacement of existing cavities with larger grain boundary cavities produced from ingot Niobium (dubbed C75 for 75 MeV gain). Reports have been made on the prototype pair of C75 cavities installed in a C50 cryomodule and the first full C75 cryomodule installed in 2017 and 2021. This paper reports on the results from the qualification of the cavities for the second C75 module in both a vertical cryostat and the commissioning results of the cryomodule in the CEBAF tunnel.

BACKGROUND

The C75 program makes use of a cavity design and tooling previously designed and optimized for high current Free Electron Laser use while employing modern cavity processing techniques with the cost saving measure of using large grain medium-to-high purity ingot Niobium (supplied by CBMM, Brazil) in place of traditional fine grain sheet Niobium to form cavities. This process is described in [1, 2] and their associated references and will not be covered herein other than to note that cavity production continues to be performed by Research Instruments (RI) located in Germany. End groups are cut from the cavities of the extracted original CEBAF C20 cryomodule to be refurbished and shipped to the vendor for attachment to the newly fabricated cavities. Cavities are deep drawn, electron beam welded into dumbbells, and shape corrected via a fixture prior to assembly for field flatness. Assembled C75 cavities are 8mm shorter in length than C20 cavities. (L_{C75}=0.492m) Once fabrication is completed cavities are then returned to JLab for further cavity processing, testing, and assembly.

CAVITY PREPARATION & RECIPE

Following receipt and incoming RF and dimensional inspection, the cavities receive a 100 mm bulk removal from the inner surface, followed by annealing in a vacuum furnace at 800 °C/3 h with a 3 h hold at 450 °C prior to reaching 800 °C. A 30 mm layer is removed from the inner surface by electropolishing (EP) after annealing. Afterwards, the cavities are subjected to dimensional check and adjustments, RF tuning. Finally, all the Nb flanges are lapped and etched by buffered chemical polishing (BCP), followed by ultrasonic cleaning and high-pressure water rinsing with ultra-pure water.

The bulk removal consisted of 100 mm EP for 3 of the cavities for cryomodule C75-02, whereas it consisted of 60 mm removal by centrifugal barrel polishing and 40 mm EP for the other 5 cavities for C75-02.

VERTICAL TEST AREA (VTA) RESULTS

Following treatment each cavity undergoes assembly of supporting components in an ISO Class 4 cleanroom followed by a slow pump down and leak check on a vertical test stand. Test stands are craned into a vertical cryostat which is then cooled down and filled with 2 K liquid Helium for cavity testing. Table 1 shows the test results.

Table 1: Vertical Test Results (FE Onset in MV/m, Cav. 3 was Limited by Multipacting)

Cav.	Emax (MV/m)	Limit	Qo @ Emax	FE onset	FE max. (mRad/hr)
1	22.0	Admin	1.23e10	13.9	3.37
2	18.2	Quench	1.11e10	11.4	1.90
3	15.6	MP	7.94e09	17.5	251.0
4	20.8	Cable	6.74e09	10	98.9
5	19.6	Rad.	6.18e09	10.75	1000
6	20.7	Quench	8.69e09	15	3.61
7	20.3	Admin	9.21e09	20.3	-
8	20.2	Cable	8.51e09	14	12.60

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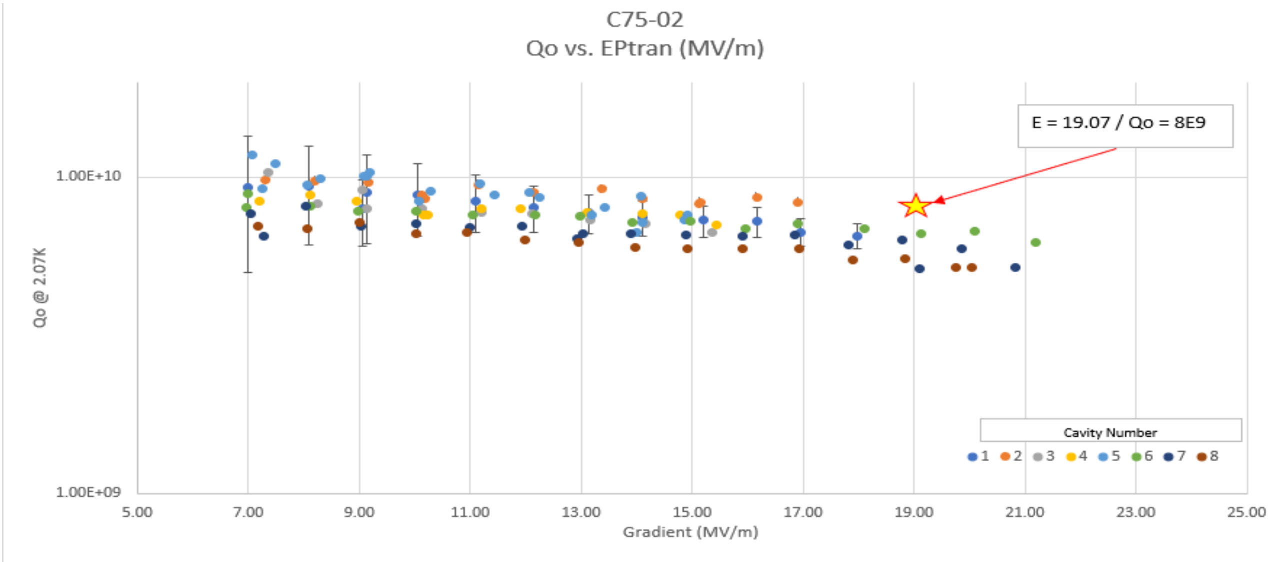

Figure 1: Cryomodule test facility (CMTF) horizontal cryostat test results.

Multipacting has shown to be an issue in C75 cavities [3], particularly with harder limits in the 17-21 MV/m range but also with softer barriers above 13 MV/m. This is the main source of the 21 MV/m administrative testing limit presently in use.

Cavity 5 was limited during testing by the level of radiation produced. Following the vertical test, the cavity was sent for High Pressure Rinse (HPR) prior to assembly to alleviate the field emitter. Average Vertical Test Area results across the zone with maximum gradients of 19.7 MV/m and average Qo of 8.83e9, both of which were within the target performance specification for the module.

HORIZONTAL TEST RESULTS

Summary of Qo vs E results based on horizontal testing may be seen Table 2 and in Fig. 1.

Table 2: Horizontal Test Results

Cav	Emax MV/m	Limit	Qo @ Emax	FE onset MV/m	FE max R/hr
1	19.0	FE	6.6e9	10.5	23.6
2	18.0	Quench	8.4e9	18.0	-
3	16.3	MP	7.1e9	11.6	0.45
4	16.3	FE	7.4e9	10.5	1.8
5	15.6	FE	7.2e9	10.5	0.37
6	21.0	Admin	6.5e9	17.0	0.18
7	21.0	Admin	5.6e9	21.0	-
8	20.4	FE	6.2e9	11.8	6.9

Horizontal testing results yielded an average Qo of 6.75e9 at the maximum deliverable cavity gradient, which on average was 18.5 MV/m. This Qo at Emax was below the performance target, but investigations completed while the module was in assembly show that based on previous cavity testing and numerical simulations that a C-75 style cavity may plan to experience a 9-30% attenuation of measured Qo in vertical test due to metallization of the fundamental power coupler (FPC) cold window [4]. VTA performance targets have been adjusting accordingly for future cavities to meet specification for future C75 assembly.

In the process of horizontal cryostat testing some cavities were further reduced in gradient to yield a 1-hour sustainable run time or 'Eop', resulting in an average gradient in the zone to 17.8 MV/m/cavity (see Table 3). This too missed installed performance targets but is in line with the reduction in Qo.

Table 3: 1-hour Sustainable Run Time or 'Eop' in the Process of Horizontal Test

Cavity SN	Position	Eop (1-hr run) (MV/m)
5C75-RI-012	Cav. 1	18.1
5C75-J-005	Cav. 2	16.9
5C75-RI-017	Cav. 3	15.4
5C75-RI-014	Cav. 4	15.1
5C75-RI-011	Cav. 5	15.0
5C75-RI-018	Cav. 6	21.0
5C75-RI-016	Cav. 7	21.0
5C75-RI-015	Cav. 8	20.2

In the end four of the cavities were field emission limited with the balance limited evenly by the 21.0 MV/m administrative limit or what appeared to be a cavity quench – which in one case appeared multipacting induced.

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IN SITU CEBAF TEST RESULTS

Following installation of the C75-02 cryomodule it was discovered in testing there were many issues attaining the available 8kW klystron power in addition to several circulator loads and two klystrons presenting with damage / insufficient isolation. After investigation, it was determined that the 5.5 kW rated circulators previously installed in the zones hosting the C75-01 and C75-02 cryomodules were not upgraded; these are scheduled to be corrected to 8kW capability in the Summer 2023 maintenance down. In addition, there was a firmware delay discovered in the klystron reflected power interlock which was isolated and removed from the LLRF 2 & 3 systems which contributed to some of the damage. Table 4 presents the in-situ test results and present settings.

Table 4: In Situ Test Results and Present Settings

Cav	Emax	Eop	Limit	Enow	Limit
1	21	19	Admin	10.0	FE
2	17.6	16.7	Quench	15.0	Pwr limited
3	21	20.5	Admin	14.1	Beam instability
4	21	20.5	Admin	18.0	Beam instability
5	21	20.5	Admin	18.0	Beam instability
6	21	21	Admin	15.0	BLVF at 17
7	22	22	Admin	16.9	Beam instability
8	20	11.5	BLVF	9.0	BLVF

Deliverable gradient was again surveyed in situ with much better results. Six of the cavities were tested up to the 21 MV/m administrative limit, with one of those 6 allowed to be tested at 22 MV/m. Of the remaining 2 cavities one was quench limited to an Emax of 17.6 and the other limited by a downstream vacuum fault. These cavities were then downgraded in 0.5 MV/m increments until they were able to achieve a stable 1-hour run – individually first, then in concert.

Table 5: In-situ Q_o, Q_{ext}, and Field Emission Survey

Qo	Qexternal	FE Onset	Max Dose (R/hr)
*	2.01E+07	11.8	21.1
*	1.98E+07	17.2	0
*	1.77E+07	11.5	12
*	1.57E+07	11.8	11.7
*	1.43E+07	10.9	11.7
*	3.24E+07	17.1	2.1
*	1.59E+07	22	0
*	1.56E+07	11.3	0.97

Table 5 shows the in-situ Q_o, Q_{ext}, and field emission survey. Unfortunately, the maximum dose in several of the field emitting cavities was surveyed to be worse once installed in CEBAF. Where this was simply due to running at higher gradients or due to some other complication is unclear.

A new plasma processing technique has been developed at Jefferson Lab [5, 6] and pioneered on the Jefferson Lab C100 style cavity geometry. T. Powers et al. have developed a novel plasma processing technique for use with C100 cavities at Jefferson Lab. Plasma processing is a known method to be used for the surface removal of hydrocarbons. It makes use of ionized Oxygen in a process gas (here - Argon) which will then react chemically with the hydrocarbons present forming combustion products (CO, CO2, H2O, etc.). The waste gases are then exhausted from the environment through the constant flow of the process gas. The plasma is initially ignited through a TESLA-style HOM coupler antenna installed in the C100 cavities via localized RF sources and amplifiers. Through shifting frequencies and transverse electromagnetic modes, one is able to target specific cells in the cavity for the reaction / processing.

Its application to C75 style cavities is presently under study for application to alleviate some of the field emission burden experienced.

While Q_{ext} data was extracted for C75-02 following installation, a survey of Qo vs E was unfortunately canceled due to limited time in favor of beam production for nuclear physics and has not yet been revisited. Heat load management is presently executed using the CMTF Q_o test values.

ENSEMBLE PERFORMANCE

To date a compliment of 18 total C75 style cavities have been installed into the CEBAF SRF linacs. (see Table 6) Two cavities served as proof-of-principle prototypes encapsulated in the C50-13 cryostat, and eight cavities each in modules C75-01 and 2. The cavities contained within C50-13 are constrained in their operation by the original CEBAF RF Contol Module LLRF system, which is more than 30 years old. [7] Administratively cavities using this control system are nominally limited both administratively and in performance to 14 MV/m. From there C50-13 cavity 1 has been systematically derated for the arc trip rate, while cavity 2 has experienced much the same with the quench fault rate to maintain a favorable overall 48-hour fault rate – which is the Figure of Merit to CEBAF Operations.

The other 16 installed cavities are controlled by a modern digital LLRF control system with good channel-to-channel isolation. [8, 9] Of these:

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Table 6: Ensemble Cavity Performance

						CMTF							CEBAF					
							FE	MaxDose					FE	MaxDose	CEBAF	Online	Present	Present
	Cavity	SN	Emax	Limit	Eop	Qo CMTF	onset	(R/hr)	Emax	Eop	Q FPC	Qo	Onset	(R/hr)	Limit	Date	Gradient	Limit
C50-13	1L13-1	5C75-001	19.1	Quench	18.6	7.60E+09	12.8		19	18.3	1.26E+07	7.60E+09	12.8	0.8	Quench	11/13/17	8.8	Fault rate mgmt
(LLRF1)	1L13-2	5C75-003	14.2	Quench	13.7	7.70E+09	10.9		14.3	14.3	1.89E+07	7.70E+09	10.4	0.1	Quench	11/13/17	8.0	Quench Rate Mgmt
	1L05-1	5C75-RI-008	18.4	Quench	18	6.70E+09	-	0	13.9	13	1.10E+07	7.00E+09	-	-	Quench	07/28/21	12.5	Beam loading/Power
C	1L05-2	5C75-J-004	16.7	Quench	10.3	8.70E+09	8.2	27	17.5	17	1.70E+07	2.40E+09	9.7	20.2	Quench	07/28/21	13.4	Beam loading/Power
7	1L05-3	5C75-RI-001	18.5	Quench	18.1	6.80E+09	13.2	0.04	18.3	17.8	2.50E+07	6.10E+09	-	0	Quench	07/28/21	18.0	Beam instability
5	1L05-4	5C75-RI-003	21	Admin	17.7	7.00E+09	13	1.7	21	21	1.80E+07	5.80E+09	14.8	0.16	Admin	07/28/21	19.0	Beam instability
-	1L05-5	5C75-RI-002	17.8	Quench	15.2	6.90E+09	11.1	0.9	18.6	17.5	2.20E+07	6.90E+09	12.7	0.84	Quench	07/28/21	14.8	Quench
0	1L05-6	5C75-RI-005	18.5	Quench	18	6.90E+09	-	0	18.5	18	1.60E+07	6.10E+09	-	0	Quench	07/28/21	18.7	Quench
1	1L05-7	5C75-RI-007	18.7	Quench	18.1	7.80E+09	-	0	21	20.5	1.90E+07	5.50E+09	14.2	0.45	Admin	07/28/21	15.0	Beam loading/Power
(LLRF3)	1L05-8	5C75-RI-006	21.1	Admin	20.6	8.00E+09	16.3	0.1	21	21	1.70E+07	6.10E+09	15.5	0.42	Admin	07/28/21	12.7	Beam instability
	1L10-1	5C75-RI-012	19	FE	18.1	6.60E+09	10.5	23.6	21	21	2.01E+07	***	11.8	21.1	Admin	06/03/22	10.0	Field Emission
C	1L10-2	5C75-J-005	18	Quench	16.9	8.40E+09	-	0	17.2	16.7	1.98E+07	***	-	0	Quench	06/03/22	15.0	Power limited
7	1L10-3	5C75-RI-017	16.3	Quench	15.4	7.10E+09	11.6	0.45	21	20.5	1.77E+07	***	11.5	12	Admin	06/03/22	14.1	Beam instability
5	1L10-4	5C75-RI-014	16.3	FE	15.1	7.40E+09	10.5	1.8	21	20.5	1.57E+07	***	11.8	11.7	Admin	06/03/22	18.0	Beam instability
-	1L10-5	5C75-RI-011	15.6	FE	15	7.20E+09	10.5	0.37	21	20.5	2.18E+07	***	10.9	11.7	Admin	06/03/22	18.0	Beam instability
0	1L10-6	5C75-RI-018	21	Admin	21	6.50E+09	17	0.18	21	21	3.10E+07	***	17.1	2.1	Admin	06/03/22	15.0	BLVF at 17
2	1L10-7	5C75-RI-016	21	Admin	21	5.60E+09	-	0	22	22	1.56E+07	***	-	0	Admin	06/03/22	16.9	Beam instability
(LLRF3)	1L10-8	5C75-RI-015	20.4	FE	20.2	5.20E+09	11.8	6.9	11.5	11.5	1.58E+07	***	11.3	0.97	BLVF	06/03/22	9.0	BLVF

- Two cavities are limited by their contribution to tripping a vacuum ion pump located on the downstream warm girder between cryomodules. (C75-02 cav. 6 & 8)
- One cavity field emission limited. (C75-02 cav. 1)
- Two cavities (C75-01 cav. 5/6) are quench rate limited.
- The remaining 11 cavities are limited by available power, resulting in instabilities which telegraph onto the beam which are visible to the operators.

This distribution of issues is of course clear evidence that the circulators in those two zones need to be replaced. Additionally, it is reasonable to expect some CW quench processing may be required to recover any gradient obviated by multipacting in the interim since these cavities were last pushed up to their Eop / 1-hour run gradients. If necessary, the zones may be low temperature cryocycled to 25 K (above T_c) and then 2 K again to recover Qos.

Other Phenomena of Interest

Observation of cavity microphonics has yielded two interesting behaviors observed. The first of which is an atypical microphonic outburst. On some motions of the mechanical tuner an outburst seems to present as seen on the Fig. 2. These events seem to occur on the order of every several hours per cavity, though not every time tuners move. (see Fig. 2)

In addition, C75 zones are constructed with each pair joined and then connected to the neighboring pair with a bellows. An additional coupled microphonics mode has been observed as may be seen in Fig. 3.

This coupled microphonics mode seems to present on its own periodically and may seemingly be remedied by the motion of one of the two tuner mechanisms of the afflicted cavity pair. This seems to destroy the coupled oscillation and restore the pair to its normal state.

Further study of these microphonic modes is required, as well as possible methods of their mitigation.

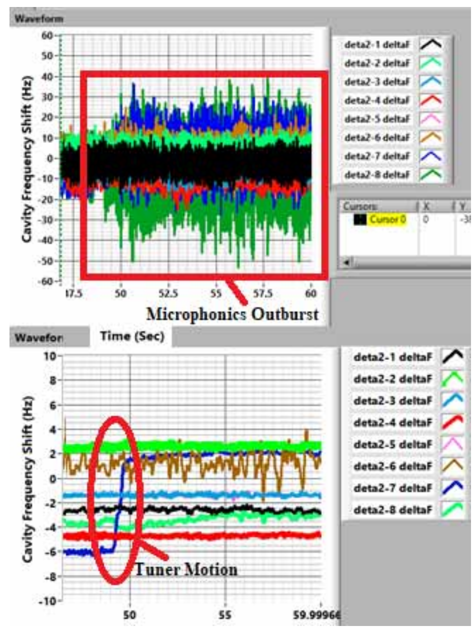

Figure 2: A single tuner microphonics event.

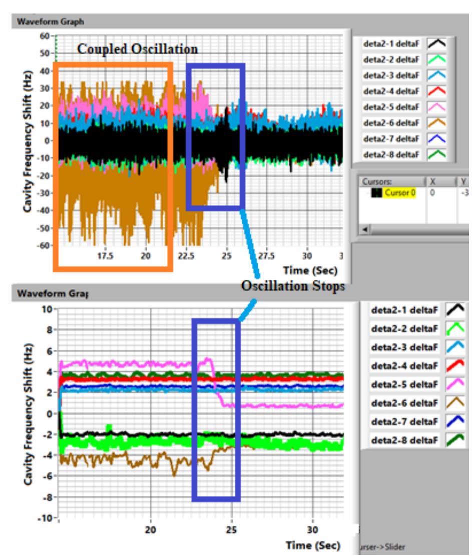

Figure 3: A coupled oscillation in a cavity pair.

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Extraction of a Gradient Degradation Rate

Starting in 2012 [10] and periodically since CEBAF Operations has examined the net gradient behavior of each cavity generation for degradation due to arcing, field emission, thermal cycling, etc. The authors desire to extract a similar figure for the C75 cavities once the power limiting behavior ceases masking other gradient limiting behaviors.

CONCLUSION

Many challenges have presented themselves in the installation of the second C75 module and evaluation of the full C75 cavity complement. Despite the issues, there is a clear maintenance path forward in the replacement of the 2 C75 zone's circulators followed by evaluation of both multipacting and microphonics disturbances in those zones with the increased amount of available power. Field emission mitigation is known to be an eventual (if not present) issue and application of the new plasma processing remediation method is already under investigation for application.

Should activities such as low temperature cryocycling, localized microphonics measurements, or Q_o measurements on C75-02 be required they are capable of being scheduled and executed with appropriate coordination on regular biweekly maintenance days.

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