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COMMISSIONING OF THE PROTOTYPE C75 CAVITIES IN A CEBAF CRYOMODULE*

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Abstract

Prototype cavities have been built at Jefferson Lab to increase the energy of future refurbished CEBAF cryomodules to 75 MeV in the most cost efficient way. Three such cavities, named "C75", have been built from ingot Nb material of different purity and have been processed and tested in a vertical cryostat. The two better performing cavities have been assembled into a "cavity pair" and installed in the latest C50 cryomodule refurbished in 2017. The cryomodule was installed and commissioned in CEBAF. The results from the commissioning of the C75 cavities, compared with the original CEBAF cavities, are presented in this article. The vertical test performance of the C75 cavities was preserved in the cryomodule with one of the cavities achieving the performance specification of an accelerating gradient of 19 MV/m with a quality factor of ~8×10^9 at 2.07 K. The performance in terms of microphonics and tuner operation was similar to that of original CEBAF cavities, as expected, and the high-order modes are properly damped. The quality factor of the two C75 cavities was the highest achieved in a CEBAF cryomodule, possibly due to the better magnetic flux expulsion of ingot Nb than standard fine-grain Nb.

INTRODUCTION

Three prototype 5-cell, 1497 MHz cavities from ingot Nb material with RRR ranging from 114 to 496 were built, processed and tested at Jefferson Lab for a future "C75" cryomodule. These cavities would operate at an accelerating gradient of 19 MV/m in order to provide an energy gain of 75 MV in the CW linacs of CEBAF [1].

The prototype cavities were limited by quenches at gradients between 11 – 20 MV/m due to defects in some of the equatorial electron beam welds. The two best cavities were assembled into a cavity pair to be installed in the cryomodule "C50-13". Original CEBAF cryomodules consists of four sections ("cryounits"), each containing a pair of cavities, which are independently assembled and then connected together to form an 8-cavity cryomodule.

CRYOMODULE ASSEMBLY

A long standing issue with cavities installed in original CEBAF cryomodule is a reduction by a factor of ~2 of the cavities' quality factor, compared to the values measured in a vertical test cryostat at the same He bath temperature. As it was done for cryomodule C50-12 [2], three cryogenic flux-gate magnetometers (FGMs) were epoxied to one of the cavities (5C75-001) to monitor the residual magnetic field during the cryomodule assembly. The location/orientation of the sensors on cavity 5C75-001 is shown in Fig. 1. The sensors are located inside the innermost magnetic shield, which was added to all cavities assembled in cryomodule C50-13 to reduce the remanent magnetic field at the cavity location to <10 mG. Components near the cavities were surveyed for their surface magnetic field and demagnetized when the field exceeds magnetic hygiene criteria.

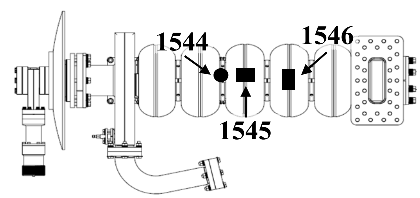

Figure 1: Location, orientation and serial number of three FGMs installed on cavity 5C75-001.

The assembly steps for each cryounit (CU) include the attachment of the cold tuner and cavity magnetic shield, welding of the stainless steel He vessel to the end dishes, installation of a secondary magnetic shield, multi-layer insulation and thermal shield and finally sliding the assembly into the cryounit vacuum vessel which also has the outermost magnetic shield inside. Figure 2 shows a picture of the C75 pair with tuner and cavity magnetic shield installed. During cryounit assembly, the cavity pair was held under static vacuum.

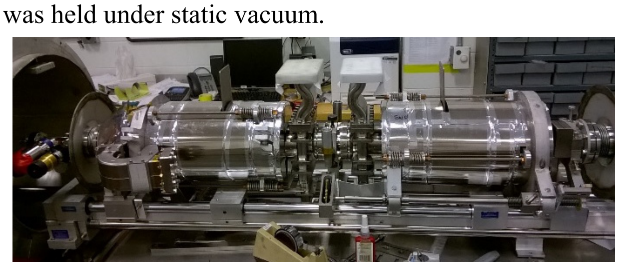

Figure 2: Picture of the C75 cavity-pair with innermost magnetic shield and cold tuner.

After four assembled cryounits are ready on the assembly rail, they are connected together at the beamline and at the He circuits. Figure 3 shows the evolution of the remanent magnetic field measured by the three FGMs, B_{res}, after cryounit assembly, after TIG welding of He circuit pipes between adjacent cryounit, after TIG welding of the vacuum vessel bridging sections between adjacent cryounits and after installation in the CEBAF tunnel. The

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data show that the TIG welding operations caused a significant increase of the remanent field, up to ~50 mG. A demagnetization scheme for C20/C50 cryomodules is being investigated with the expectation of reducing the magnetization caused by welding as per experience with LCLS-II cryomodules [3].

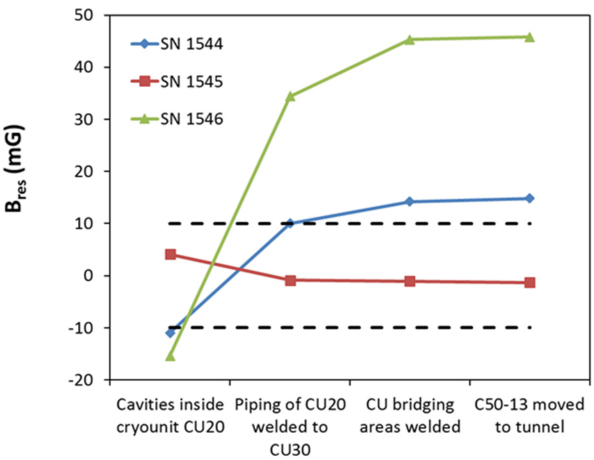

Figure 3: Remanent magnetic field measured during cryomodule assembly and installation in the CEBAF tunnel.

CRYOMODULE COMMISSIONING

The location of the two C75 cavities in C50-13 is shown schematically in Fig. 4. The remaining six cavities ("C50") are 5-cell cavities of the original Cornell CEBAF shape which have been processed with a 600 °C/10 h vacuum anneal, 25 µm removal by electropolishing and high-pressure water rinse.

The cryomodule was commissioned in the CEBAF tunnel. The cooling rate at 9.25 K (the critical temperature of niobium) of 5C75-001 was ~0.44 K/min. The temperature was measured with silicon diodes located on the HOM elbows, inside the He vessel. Unfortunately, the data acquisition to log the signal from the FGMs malfunctioned during cooldown.

The operation of the cold tuners on the C75 cavities was without issues. Hysteresis curves shown in Fig. 5 for the two C75 cavities and two C50 cavities show similar behavior. Differences may be related to the cavities' stiffness.

The quality factor, Q, was measured with the pressure rate of rise method as a function of the accelerating gradient, E_{acc}, at ~2.11 K. A plot summarizing $Q(E_{acc})$ scaled to 2.07 K for the two C75 cavities is shown in Fig. 6 along with the radiation measured at the beamline supply end of the cryomodule. The temperature scaling of the quality factor was based on the $Q(T)$ dependence measured for each cavity during testing in the vertical cryostat. The maximum E_{acc} for cavity 1 (5C75-001) could be raised up to 19 MV/m a few days later after field emission was fully processed to a non-detectable dose rate. Scheduling of the accelerator operations prevented us from measuring Q at the highest gradient. A summary of the performance of all the cavities in C50-13 is given in Table 1. It is important to notice that the two C75 cavities have the highest Q of any cavity measured in an original CEBAF cryomodule, in spite of the high remanent magnetic field. This may be the result of the better flux expulsion of ingot Nb material, compared to fine-grain Nb [4].

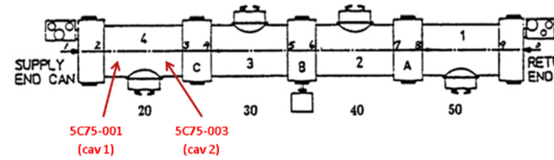

Figure 4: Schematic drawings of the original CEBAF cryomodule comprising of 4 cryounits. The two C75 cavities are at positions 1 and 2, in CU20.

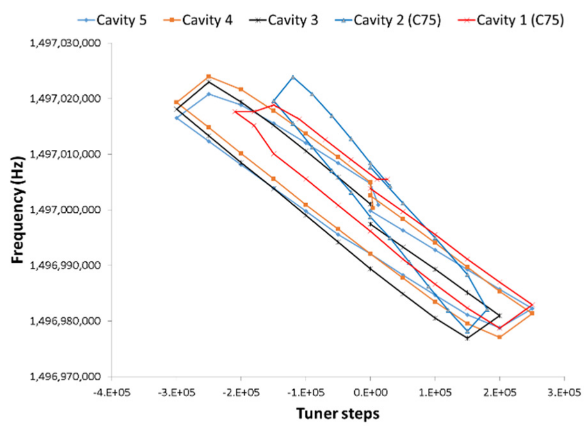

Figure 5: Tuner hysteresis curves for C75 cavities and three C50 cavities.

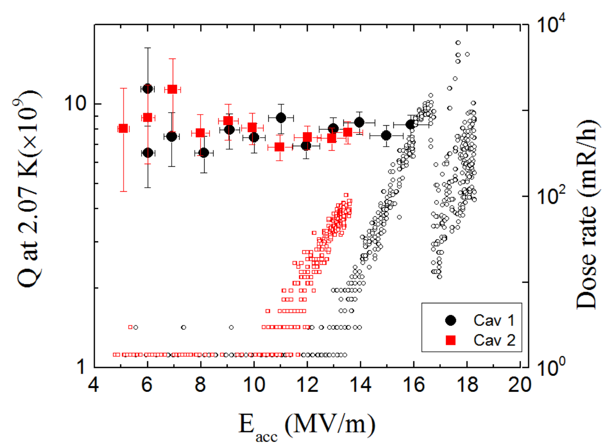

Figure 6: Q vs. E_{acc} scaled to 2.07 K and dose rate (empty symbols) measured from the two C75 cavities during commissioning. 5C75-001 reached 19 MV/m after field emission processing.

Microphonics measurements were done on each cavity powered through a digital low-level RF system in self-excited loop. I/Q data was recorded at 20 kS/s and converted to frequency shift, 25 seconds of data taken for

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Table 1: Performance of the Cavities in C50-13 Measured in the CEBAF Tunnel, Compared to That Measured in a Vertical Cryostat (VTA). The Q-values Are at 12.5 MV/m, Scaled to 2.07 K.

Cavity Pos.	Cavity SN	$E_{acc,max}$ VTA (MV/m)	Q VTA ($\times10^9$)	FE onset VTA (MV/m)	$E_{acc,max}$ (MV/m)	Q ($\times10^9$)	FE onset (MV/m)	Limit
1	5C75-001	19.4	9.0	17.9	19.1	7.6	12.8	Quench
2	5C75-003	13.7	8.3	9.9	14.2	7.7	10.9	Quench
3	IA274	18.3	9.6	15.6	16.6	6.5	-	Quench
4	IA345	19.9	8.5	15.0	17.4	4.3	9.4	Waveguide vacuum
5	IA366	9.2	7.6	8.5	9.2	7.0	-	Quench
6	IA351	15.1	7.8	14.1	14.0	5.8	-	Quench
7	IA038	18.0	7.0	-	16.9	6.0	-	Quench
8	IA260	17.0	6.7	10.9	15.5	4.5	7.5	Quench

each data series. Three to five data series were collected for each cavity. Figure 7 shows a summary of the results: the behavior of the two C75 cavities is within the range observed in C50 cavities. The Lorentz force detuning (LFD) coefficient was -2.6 Hz/(MV/m)^2 and -4.0 Hz/(MV/m)^2 on 5C75-001 and 5C75-003 respectively. The value of LFD for cavity 3 was -2.6 Hz/(MV/m)^2.

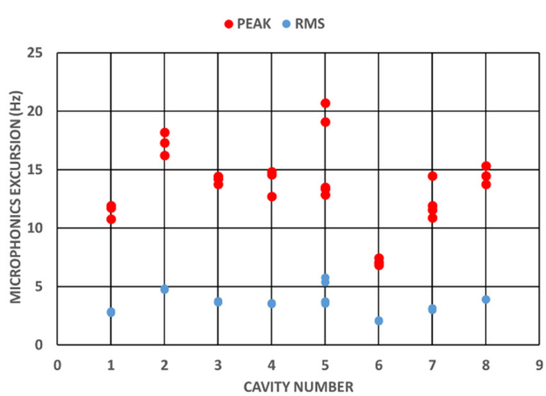

Figure 7: Peak and rms frequency detuning due to microphonics for all the cavities in C50-13. The C75 cavities are at position 1 and 2. Multiple points per cavity refer to multiple data series.

The frequencies and loaded quality factor Q_L of Higher Order Modes (HOM) were measured at 4.3 K in transmission with a Vector Network Analyzer between the “reflected power” port of the bi-directional coupler and the “cavity probe” port. The data are shown in Fig. 8 for the C75 cavities and two C50 cavities. In all cases, the HOM impedance is within specifications.

CONCLUSION

Two prototype 5-cell cavities made of large-grain, ingot Nb for the C75 cryomodule refurbishment program have been fully commissioned in the CEBAF tunnel in cryomodule C50-13. The cavities achieved the same quench fields as in the vertical tests and had a higher quality factor than standard fine-grain cavities in the same type of cryomodule, in spite of a high remanent magnetic field.

The performance of the C75 cavities in terms of tuner operation, microphonics and HOM is similar to that of C50 cavities, as expected by design. The C75 cavities have been accelerating beam in CEBAF since November 2017, without noticeable issues, at 13.5 MV/m, the maximum accelerating gradient allowed by the low-level RF system installed in the linac zone.

Two additional prototype cavities are being built “in house” to improve the cavity fabrication and eight more cavities are being fabricated by Research Instruments, GmbH, all made from medium-purity ingot Nb discs. Those cavities will be used to assemble the first C75 cryomodule in 2019.

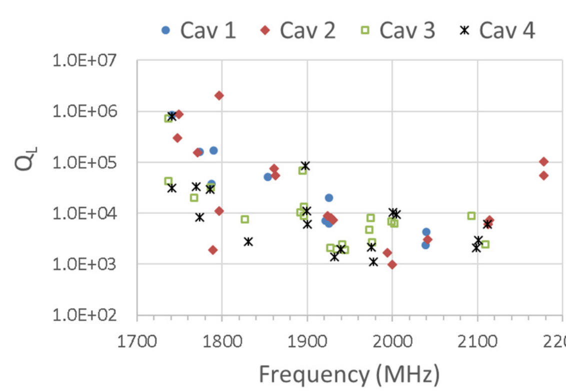

Figure 8: Frequencies and Q_L-values of HOM in C75 cavities (1 and 2) and two C50 cavities.

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