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Tuning sensitivity and stiffness of C20/C50 and C75 cavities

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1. Introduction

The C75 cavities are five-cell cavities with the same end-group geometry as those used for the original C20/C50 CEBAF cavities [1] but updated cell shape design to yield a higher cryogenic efficiency. The cell shape adopted is the same as designed for the High-Current FEL project [2]. Stiffening rings are added between mid-cells and between end-cells and end-groups at a radius which results in a tuning sensitivity close to that of C20/C50 cavities as determined by Finite Element Analysis (FEA), since the original CEBAF cavity tuner will be re-used.

This technical note describes the results from the FEA on both C20/C50 and C75 cavities and from measurements of the tuning sensitivity at room temperature on both types of cavities, with and without a newly designed magnetic shield. The cavity stiffness was also measured for both types of cavities. The C20/C50 cavity was made from standard fine-grain Nb with residual resistivity ratio (RRR) greater than 250. The C75 cavity was made from ingot Nb of RRR ~ 120.

2. FE Analysis

The FE analysis of the tuning sensitivity was done at an earlier stage of the design work, with a simple model of only the cavity and, in the case of the C75 cavity, its stiffener rings. No surrounding structure, including any part of the tuner assembly, was included in the model geometry. This also meant that the model could be condensed to an axial half-symmetry model, as shown in Fig. 1.

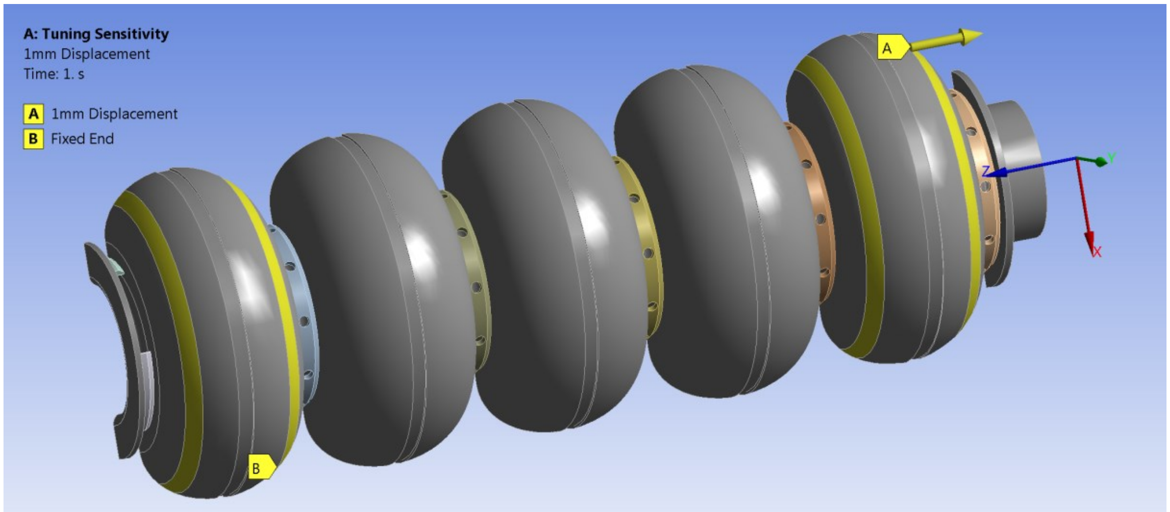

Fig. 1. Finite element model of the C75 cavity used to calculate the tuning sensitivity.

To analyze the effects of an applied tuning displacement on the resonant frequency, a series of coupled analyses are performed:

1. A high frequency electromagnetic analysis provides the accelerating mode frequency for the cavity.
2. A structural analysis yields the deformation of the cavity from an applied displacement load
3. The deformed cavity shape from step 2 is used in a second electromagnetic analysis.

The resulting frequencies from the first and last electromagnetic analyses give a Δf for the applied load.

For the cavity model, Niobium material with an elastic modulus *E* = 88.5 GPa was used [3]. Boundary conditions were applied to the tuner contact surfaces on the end cells (see yellow surfaces in Fig. 1) to calculate the cavity deformation. One end was constrained in longitudinal direction, while the other end was displaced by 1 mm. A positive (stretching) deformation was applied, although the direction is irrelevant in this linear analysis.

A similar analysis was performed on both the original C20/C50 cavity shape and the C75 cavity with stiffening rings. The results including the stiffness values of the cavity are presented in Table 1.

Table 1: Results from FEA of C20/C50 and C75 cavities to calculate the tuning sensitivity and stiffness.

Geometry	**f_1 [MHz]**	**f_2 [MHz]**	**Δf [Hz]**	**df/dl [kHz/mm]**	**Reaction Force [N]**	**Tuning Stiffness [lbf/in]**
C20/C50	1496.8	1497.6	720304	720.30	6816	38923
C75, 48mm rings	1489.5	1490.0	513284	513.28	6844	39085

It should be noted that the tuning sensitivity values from the FE analysis should not be compared to the measured sensitivity value over the entire range of displacement, since this takes into account initial nonlinear effects of slack etc. in the tuner. It is best compared to the value evaluated at the outer linear regions of the measured frequency-deformation curve (cf. Fig. 3).

3. Measurement results

An original CEBAF tuner was assembled onto two prototypes cavities, one on a C20/C50 cavity and one on a recently built C75 cavity. Each cavity was excited with an antenna inside a beam tube. The TM_{010} π-mode frequency was recorded with a Vector Network Analyzer (VNA) at the minimum of the reflection response. The displacement between the two tuner cell holders mounted on the end-cells was measured with a Keyence IL-065 laser displacement sensor, which has an accuracy of 2 μm. The tuner is actuated by turning the vertical shaft connected to the gear. The setup assembled onto the C75 cavity is shown in Fig. 2. The inner diameter of the tuner yokes used in these measurements was increased by 1 mm to accommodate for the magnetic shield.

The results from measurements of the tuning sensitivity are shown as plots of the frequency shift Δf as a function of displacement Δz in Figs. 3 and 4 for C20/C50 and C75 cavity, respectively. The tuner is designed to operate in compression and a preload corresponding to a frequency shift of $\sim$ –50 kHz is usually applied after assembly of the tuners on a cavity pair in order to operate near the linear region of the Δf(Δz) curve.

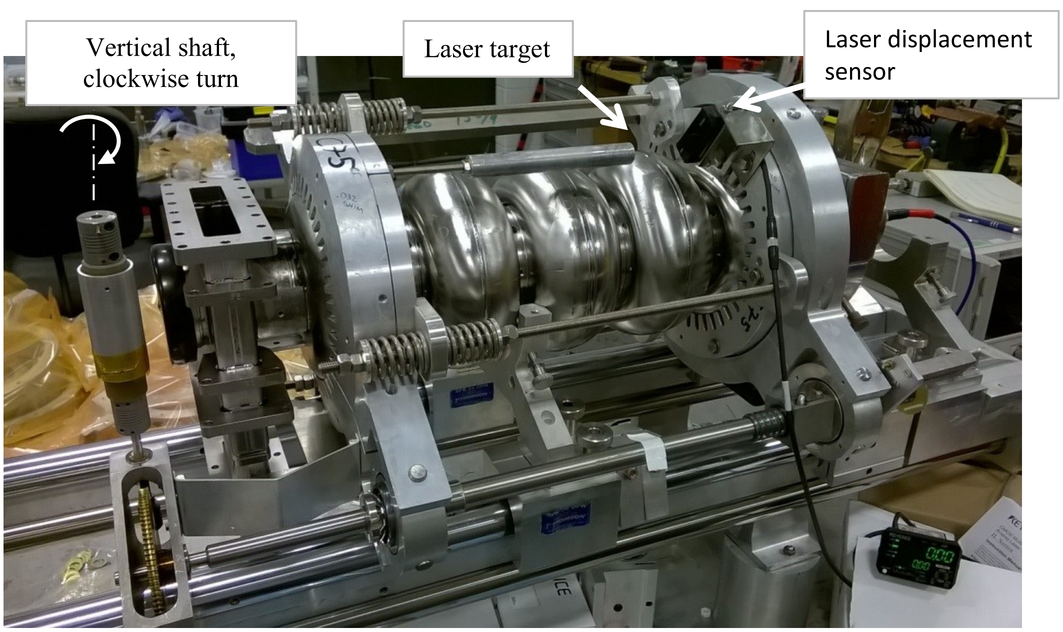

Fig. 2. Experimental setup to measure the tuning sensitivity on C75 and C20/C50 cavities without magnetic shield.

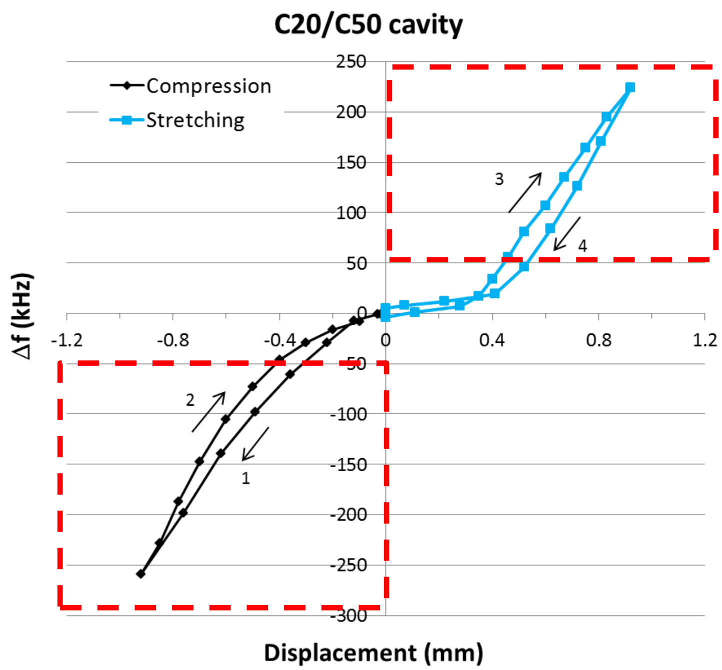

Fig. 3. Δf(Δz) measured on a C20/C50 cavity w/o magnetic shield. The numbered arrows indicate the cycle number. Only data within the dashed boxes were used to calculate the tuning sensitivity.

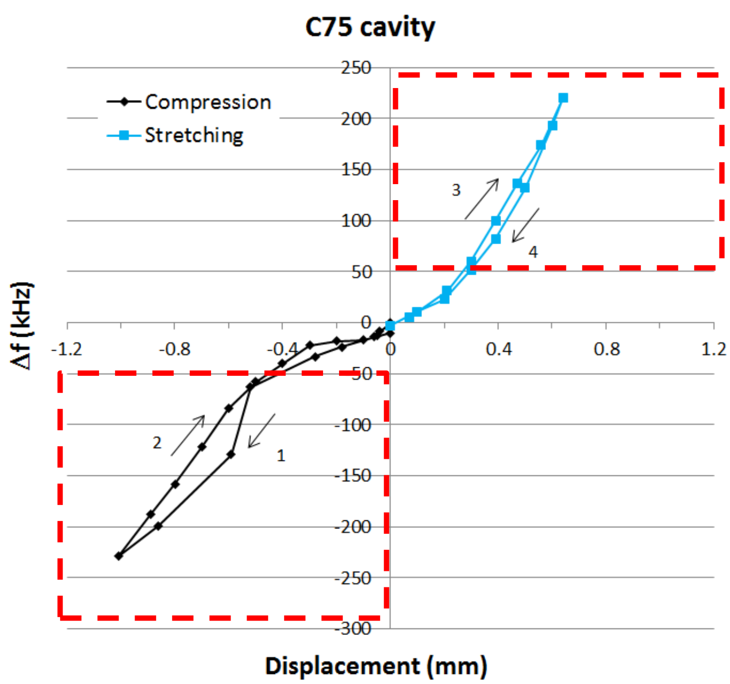

Fig. 4. Δf(Δz) measured on a C75 cavity w/o magnetic shield. The numbered arrows indicate the cycle number. Only data within the dashed boxes were used to calculate the tuning sensitivity.

The measurements were repeated with a new magnetic shield installed, as shown in Fig. 5 for the C75 cavity, to verify that it did not impact the operation of the tuner. In this case there was no space to place the laser displacement sensor and Δf was measured as a function of the number of turns of the vertical shaft. The number of turns was converted to the displacement values using the factor -0.82 mm per 100 clockwise turns, which was measured for both cavities without magnetic shield. Results are shown in Figs. 6 and 7 for the C20/C50 cavity and for the C75 cavity, respectively.

The values of the tuning sensitivity data for $|\Delta f| > 50$ kHz, averaged between the four cycles, with and without magnetic shield, are listed in Table 2. After installation of the tuners on a cavity pair during cryomodule assembly, a preload resulting in a frequency shift of ~ -50 kHz is usually applied.

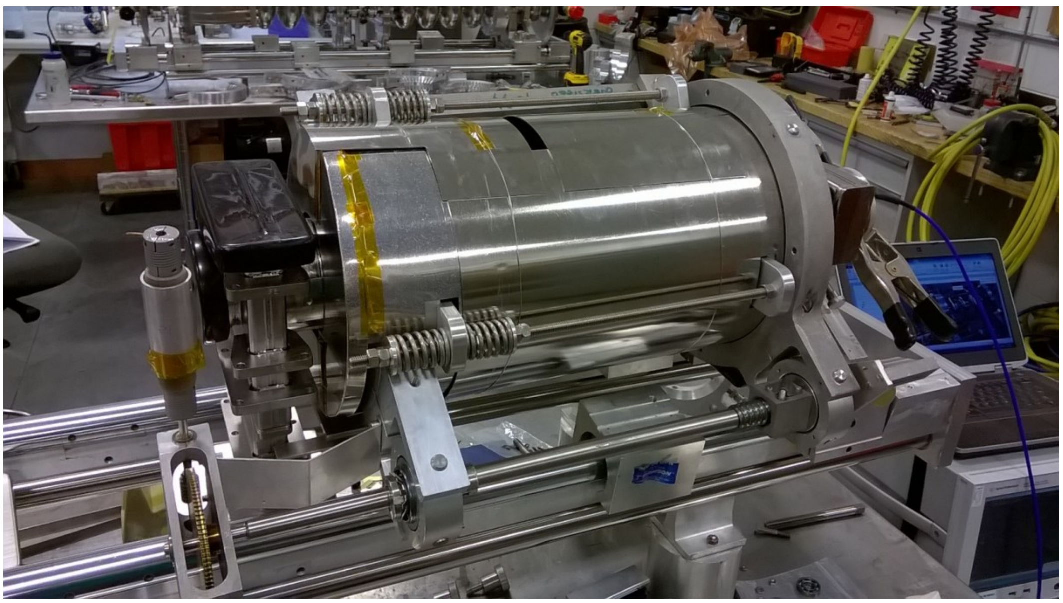

Fig. 5. C75 cavity with tuner and new magnetic shield installed.

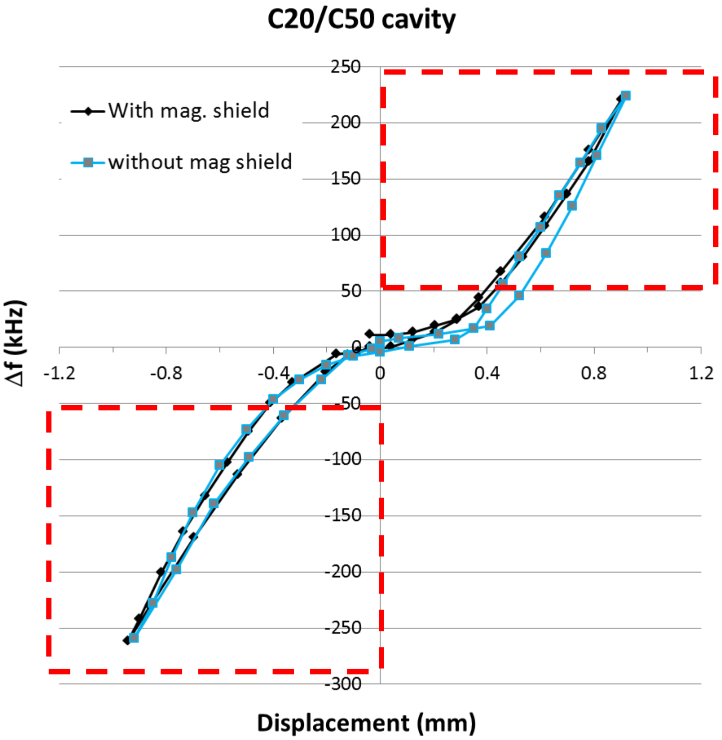

Fig. 6. Δf(Δz) measured on a C20/C50 cavity with and without magnetic shield. Only data within the dashed boxes were used to calculate the tuning sensitivity.

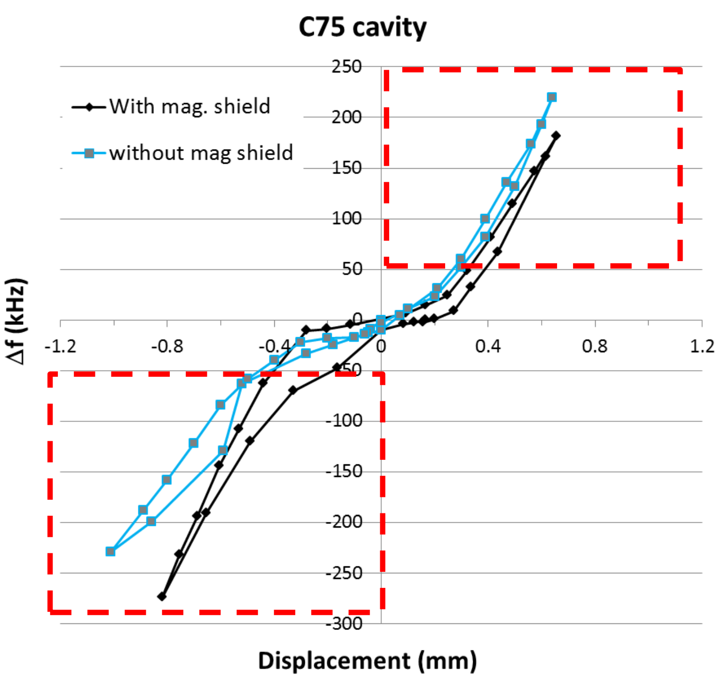

Fig. 7. Δf(Δz) measured on a C75 cavity with and without magnetic shield. Only data within the dashed boxes were used to calculate the tuning sensitivity.

Table 2. Tuning sensitivity values in the linear range of $\Delta f(\Delta z)$, averaged over four cycles, measured on a C20/C50 cavity and a C75 cavity with and without magnetic shield.

	C20/C50 cavity	**C75 cavity**
Without magnetic shield Deviation from FEA	(410 ± 50) kHz/mm -40%	(420 ± 110) kHz/mm -20%
With magnetic shield Deviation from FEA	(370 ± 40) kHz/mm -50%	(470 ± 80) kHz/mm -10%

The cavity stiffness was determined by clamping two sets of aluminum holders onto the end-cells. These holders are used for fine alignment of the side ports during CMM inspection. Each holder is made by two halves bolted together with 1/4"-20 threaded rods. The laser displacement sensor and target are mounted on the inner side of the aluminum holders. An antenna is inserted into the beam tube to measure the resonance frequency with a VNA. The cavity is then lifted with a crane and weights are hung from handles attached to the bottom holder. Fig. 8 shows a picture of the setup. The resonance frequency and the displacement between the holders are measured as a function of weight. During the test it was found that some flexing of the bolts holding the two halves of each holder did not allow reproducible measurements of the cavity displacement while hanging weights.

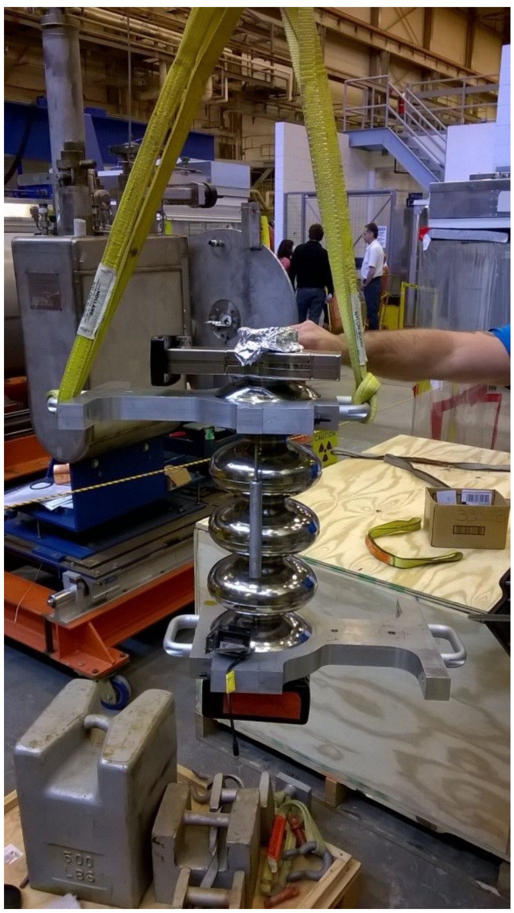

Fig. 8. Setup for measuring the stiffness of both C20/C50 and C75 cavities.

Measurements for the C75 cavity were done twice and a plot of the frequency shift, Δf, versus load, *w*, is shown in Fig. 9. A linear fit of the data indicates df/d*w* = 532 Hz/lbf for the C75 cavity and 409 Hz/lbf for the C20/C50 cavity. The cavity stiffness was calculated by multiplying df/d*w* with the weighted average of the tuning sensitivity with and without magnetic shield and the values for both cavity types are shown in Table 3.

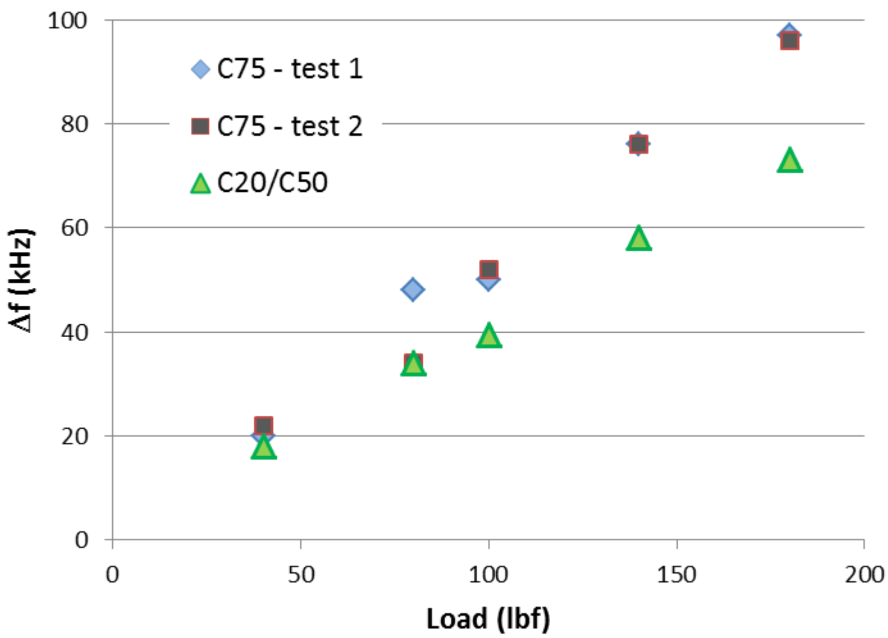

Fig. 9. Δf vs. load measured on both C20/C50 and C75 cavities.

Table 3. Average stiffness and deviation from FEA analysis for both C20/C50 and C75 cavities.

	C20/C50 cavity	**C75 cavity**
Stiffness	(24,000 ± 2,000) lbf/in	(22,000 ± 3,000) lbf/in
Deviation from FEA	-40%	-40%

4. Discussion

Both values of tuning sensitivity and cavity stiffness measured on C20/C50 and C75 cavities are significantly lower than obtained from the FEA analysis. A reason for this discrepancy might be due to the cell holders not being rigidly and firmly attached to the cavity in both tests, so that the displacement between such holders is not entirely a displacement of the cavity. Significant discrepancies among measurements and FEA analysis were also found when testing the 7-cell "High gradient" prototype C100 cavities [4]. The tuning sensitivity value of the C75 cavity has a larger standard deviation than that of the C20/C50 cavity, with and without magnetic shield. During the tuner assembly it was found that the cell holders did not fit well to the cavity cells and more shimming between the cells and the holders were needed than during assembly of the tuner onto the C20/C50 cavity, resulting in a more hysteretic tuning curve for the C75 cavity.

The purpose of the tests was to verify that the C75 cavity has stiffness comparable to that of the C20/C50 cavities, since it must operate with the same type of tuner. The experimental results showed the stiffness of the C75 cavity to be within ~10% (of the order of one standard deviation) of that of the C20/C50 cavity, validating the initial FEA analysis. The impact of the new C75 design on the microphonics level is currently being analyzed experimentally and numerically and will be presented elsewhere.

5. References

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[2] R. A. Rimmer, H. Wang, G. Wu, “Strongly HOM damped multi-cell RF cavities for high-current application”, Proc. SRF’03, Lubeck Germany.

[3] G. Ciovati et al., *Mat. Sci & Engineering A* **642** (2015) 117–127.

[4] G. Cheng and M. Wiseman, “C100 Cryomodule Niobium Cavity Structural Analysis”, JLab Tech Note TN-10-001.