MECHANICAL DESIGN OF A NEW INJECTOR CRYOMODULE 2-CELL CAVITY AT CEBAF*

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Abstract

As a part of Jefferson Lab's 12 GeV upgrade, a new injector superconducting RF cryomodule is required. This unit consists of a 2-cell and 7-cell cavity, with the latter being refurbished from an existing cavity. The new 2-cell cavity requires electromagnetic design and optimization followed by mechanical design analyses. The electromagnetic design is reported elsewhere. This paper aims to present the procedures and conclusions of the analyses on cavity tuning sensitivity, pressure sensitivity, upset condition pressure induced stresses, and structural vibration frequencies. The purposes of such analyses include: 1) provide reference data for cavity tuner design; 2) examine the structural integrity of the cavity; and 3) evaluate the 2-cell cavity's resistance to microphonics. Design issues such as the location of stiffening rings, effect of tuner stiffness on cavity stress, choice of cavity wall thickness, etc. are investigated by conducting extensive finite element analyses. Progress in fabrication of the 2-cell cavity is also reported.

CEBAF NEW INJECTOR CRYOMODULE CAVITIES

Presently in the injector section of CEBAF there is a "Quarter Cryomodule", which has two 5-cell cavities. With the upgrade of operating energy from 6 GeV to 12 GeV, a few options for the booster cavity layout have been studied [1] and the 2-cell plus 7-cell cavities layout is deemed desirable. The demanded field amplitude for the 7-cell cavity is around 13 MV/m. An economic decision is made to refurbish a low loss JLAB Renascence cryomodule [2] 7-cell cavity, which is capable to provide 17-21 MV/m accelerating field amplitude, to be used in the new Injector Cryomodule. The 2-cell cavity is a new design based on the low loss cavity shape and is expected to provide approximately 4.6 MV/m accelerating field.

2-CELL CAVITY MECHANICAL DESIGN

The 2-cell cavity is made of high RRR fine grain niobium. Basic mechanical properties used in all design analyses are listed in Table 1. Note that the 2-cell cavity niobium material is the same as SNS cavity material and the cavity will be baked at 600 °C for 10 hours. Although niobium is not a "code material", the ASME Boiler & Pressure Vessel Code (BPVC) rules are referenced during the pressure induced stress analysis for the 2-cell cavity. The allowable stresses are determined per BPVC rules, i.e. the allowable stress is the lesser of 2/3 of yield strength or 1/3.5 of the tensile strength.

Among the major cavity mechanical design considerations, the choice of cavity wall thickness is mainly dictated by the upset condition pressure induced stress. The wall thickness also affects the cavity stiffness, tuning and pressure sensitivities, as well as vibration natural frequency. Similar theory applies to the option of using ring shape stiffeners. All mechanical design analyses are performed in ANSYS®. The tuning and pressure sensitivity calculations involve electromagnetic to structural coupled field analysis technique. Each design topics is addressed in a bit more details in the following sections.

Table 1: High RRR Niobium Mechanical Properties [3-5]

Properties	Room Temperature	Cryogenic Temperature
Young's Modulus, psi	1.49e7	1.79e7
Poisson's Ratio	0.38	0.38
Density, lb/in^3	0.31	0.31
Yield Strength, ksi	9.5	83.7
Tensile Strength, ksi	26.3	118.8
Allowable Stress, ksi	6.33	33.9

2-CELL CAVITY STRUCTURAL STRESS

Three loading conditions are examined for the stress state in the 2-cell cavity: 1) 2.2 atm pressure at room temperature (R.T.) simulating pressurization during the cryomodule cool down process, 2) 5 atm pressure at cryogenic temperature (C.T.) simulating pressurization caused by upset conditions [6], and 3) 5 atm pressure with 300 μm tuning displacement. The pressure chamber surrounding the niobium cavity is formed by the interior of a helium vessel and the cavity external surfaces. The helium vessel for this 2-cell cavity is made of stainless steel and has one bellows to mitigate the thermal stress developed during cool down and caused by the mismatch of expansion coefficients between niobium and stainless. The bellows also permits tuning of the cavity without holding up against an otherwise stiff helium vessel. Outside the helium vessel, a scissor-jack tuner is mounted. The helium vessel bellows and tuner are simulated as springs in the cavity stress analysis model. The bellows' longitudinal spring constant is relatively small. The tuner's warm and cold stiffnesses are analysed separately on a preliminary tuner design model.

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Two cavity wall thickness values are considered in the stress analyses: 3 mm and 4 mm. As to the stiffening rings, three design options, i.e. no rings, one ring between 2 cavity cells and 3 rings (2 added between the cells and helium vessels), are investigated. It is found that at least 3 rings are needed to reduce the pressure induced stress. The stiffening rings' radial locations are studied and it is found that large diameter rings would increase the cavity stiffness hence reduce the stresses, however, when the rings are too big, electron beam welding of these rings could affect the braze joint between niobium cavity and stainless steel helium vessel. In addition, if the cavity and helium vessel assembly is too stiff, tuning of the cavity will become difficult. The stiffening ring diameter is finally decided to be consistent with that for the 7-cell cavity. Table 2 shows the stress results for the 2-cell cavity with 3 stiffening rings and 3 mm or 4 mm wall thickness. Based on Table 2, the 4 mm cavity is selected. Note that the peak stresses typically occur at sharp corners where the stiffening rings are welded to the cavity. Such stresses are disregarded due to finite element model singularities that are incredible. The "body stress" is taken at "hotspots" that are away from the singularity points. Figure 1 shows the stress for the 4 mm thick cavity subjected to 2.2 atm pressure at R.T.

Table 2: Pressure Induced Stresses in Cavity with Different Wall Thicknesses

Cases	Tuner Stiffness (lbf/in)	Cavity stress (psi)	3 mm	Acceptable?	4 mm	Acceptable?
5 atms at C.T.	88,001	peak stress	22,036	-	18,656	-
		body stress	18,890	Yes	16,001	Yes
5 atms C.T. with 300 μm tuning	88,001	peak stress	24,756	-	23,104	-
		body stress	21,225	Yes	19,812	Yes
2.2 atms at R.T.	79,700	peak stress	9,177	-	7,850	-
		body stress	7,905	No!	6,172	Yes

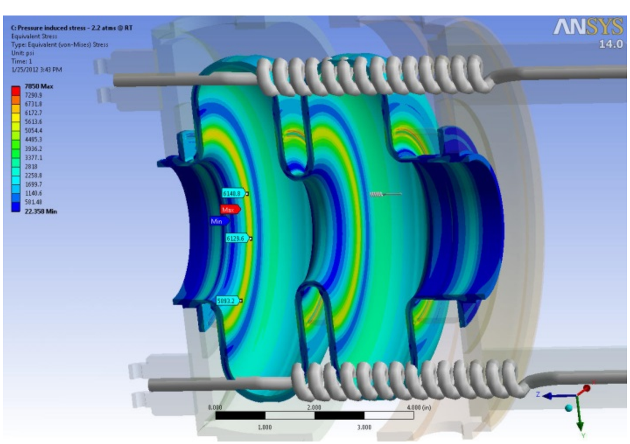

Figure 1: Stress in the 2-cell cavity (4 mm thick with 3 stiffening rings) subjected to 2.2 atm pressure at R.T.

2-CELL CAVITY TUNING AND PRESSURE SENSITIVITIES

The scissor-jack tuner exerts tuning force to the cavity through two pairs of tuner tabs that are mounted on the end plates of the helium vessel. The change of cavity electromagnetic frequency versus displacement between the pairs of tuner tabs is defined as the tuning sensitivity for the 2-cell cavity. Knowing the tuning sensitivity is important in tuner design as well as tuner operation.

Another important characteristic of the 2-cell cavity is its pressure sensitivity, that is, cavity electromagnetic frequency change with respect to helium vessel pressure fluctuation. Based on operational experiences, a ±0.1 torr pressure fluctuation is typical [7]. It is also learned from operational practices that such pressure fluctuation does not occur in a rapid manner. This means that the slow tuner can rectify the frequency shift in time. Ideally, one would want to control the pressure sensitivity to be a quite small number. This is affected by a number of factors, among which the size of the helium vessel bellows is crucial. The 2-cell cavity's helium vessel adopts a nominal 10″ diameter bellows design. This size of bellows is also used in Jefferson Lab's 12 GeV upgrade cryomodules (also called C100 cryomodules). It is expected that the pressure sensitivity of the 2-cell cavity to be at a similar level as C100 cryomodule cavities. Note that the stainless steel helium vessel and the 2-cell cavity (4 mm wall thickness and having 3 stiffening rings) itself are quite stiff, which helps in reducing the pressure sensitivity.

Coupled field analyses are carried out to solve for the tuning and pressure sensitivities. In principle, the model includes the vacuum volume that is enclosed by the niobium cavity. For tuning sensitivity analysis, the cavity and helium vessel are included in the model. For pressure sensitivity analysis, the tuner (simulated as a couple of equivalent springs) is also included. Frequency of the undeformed vacuum volume is calculated first. Then tuning displacement or pressure load is applied to the cavity and helium vessel. The niobium cavity deforms and the deformed shape of cavity is used to alter the vacuum volume. In the analysis model, the cavity and vacuum volumes share common interfaces so that nodal displacements at interfacial nodes can be conveniently transferred from the cavity to the vacuum. At last, the "deformed" vacuum is used to calculate a new frequency. The difference between the before and after structural deformation frequencies is then divided by the tuning distance or pressure applied to calculate the corresponding sensitivities.

For the 4 mm thick 2-cell cavity equipped with 3 stiffening rings, the tuning sensitivity is calculated to be 2.63 MHz/mm. Based on this, to achieve a coarse tuning range of 600 kHz, 228 μm tuning is needed. In the mechanical designs, this tuning distance is rounded up to 300 μm to be conservative. The cavity and helium vessel assembly's cold stiffness is estimated to be 8.93 N/μm.

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Figure 2: Fabricated 2-cell cavity major components.

The pressure sensitivity of the 2-cell cavity is calculated to be 382 Hz/torr. For the C100 7-cell cavity (3mm wall thickness, no stiffening rings), the measured pressure sensitivity is around 320 Hz/torr. So, the new 2-cell cavity's pressure sensitivity is comparable to that of the C100 7-cell cavity.

CAVITY VIBRATION FREQUENCY

To mitigate the detrimental effects brought by microphonics, "one should push the mechanical resonance frequencies as high as possible…" [8] In the 2-cell cavity design, 4 mm wall thickness and 3 stiffening rings are selected not only for resistance to the pressure loads, but also for high vibration frequencies. The 2-cell cavity is hosted by a helium vessel, which is supported by eight Nitronic rods in the transverse direction and two Nitronic rods in the axial (parallel to beam axis) direction. All rods are mounted to a spaceframe, which is bolted to a vacuum vessel that is anchored to the ground. Vibration analysis is very sensitive to the boundary conditions employed. However, it is impractical to build a mathematical model that reflects a real cryomodule's conditions precisely. In the 2-cell cavity vibration model, the vacuum vessel, spaceframe and Nitronic rods are assumed to be stationary, although in reality they pass environmental vibrations to the helium vessel and niobium cavity. The point is to examine the cavity's natural resistance to vibrational resonance. Therefore, the boundary conditions are that at the helium vessel end where 4 transverse rods and 2 axial rods exist, fixed support boundary condition is applied. At the other end where only 4 transverse rods exist, the helium vessel is fixed in transverse directions only. Basically, the cavity vibration model has a set of fixed-guided boundary conditions. The lowest vibration mode of the 2-cell cavity is found to be an axial mode, i.e. parallel to beam axis extension/compression oscillation, with a frequency of 218 Hz, which is much higher than the design criteria of 100 Hz. The 2-cell cavity is thus deemed as being robust in terms of its resistance to low frequency vibration resonances.

CAVITY FABRICATION

Fabrication of the 2-cell cavity has started. As shown in Fig. 2, major components such as the fundamental power coupler endgroup, end half cells, dumbbell, HOM endgroup, etc. are made. Special tools to help in dumbbell trimming and stiffening ring electron beam welding were designed and made. The amount of trimming on these components are determined per RF measurements. The 2-cell cavity is aimed to be finished in the Fall of 2013 and qualification tests will follow.

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