MECHANICAL CAVITY DESIGN FOR 100MV UPGRADE CRYOMODULE*

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Abstract

To achieve up to 6 GeV, each cryomodule in the CEBAF accelerator currently provides about 30 MV of acceleration. To raise the accelerator energy to 12 GeV, ten additional cryomodules, each capable of providing over 100 MV of acceleration, are required. A prototype of the 100 MV cryomodule has been designed, is presently under construction, and will be completed in 2004. This prototype cryomodule comprises two new cavity designs, four cavities of the low loss design and four cavities of the high gradient design [1,2].

Although the cavity shapes were designed for their RF properties, the mechanical implications must be considered. In addition to the new cavity shapes, changes have also been made to the cavity end dish assemblies, weld joints, and stiffening rings. This paper will present the results of the stress and vibration analyses used for designing the cavity string.

STRESS ANALYSIS

Two critical load cases were examined, one for the warm cavities and one for the cold. The highest stresses in the cold cavity will result from the superposition of tuning and pressure loads. The cavity may be displaced outwards by as much as 2 mm during tuning, placing the cavity in tension; in theory, this could coincide with a pressure load of up to 4 atmospheres in case of system failure.

For the warm cavity, the greatest stresses will most likely occur during alignment. The cavities are held just outside the end cells and force is applied to the beam pipe flange to bring the beam pipe into alignment for assembly.

Model Description

During the course of the cavity design, several different configurations were considered and analyzed for both the low-loss (LL) and high-gradient (HG) cavities. Figure 1 reflects the final design of the low-loss cavity.

For the analysis of the cold cavity, a two-dimensional part was meshed with axisymmetric parabolic elements. As shown in Figure 1, blue elements are titanium, red elements are niobium-titanium, and green elements are RRR niobium.

For the warm analysis, only the beam pipe was modeled (Figure 4) since it was assumed the cavity would be fully fixed just outside the cells and only the beam pipe would deform. A half-model was used and meshed with parabolic solid elements.

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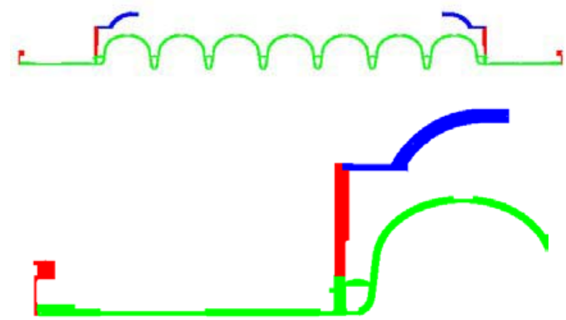

Figure 1: Low loss cavity mesh

Material Properties

Material properties used in the models are shown in the tables below.

Table 1: Material Properties of Niobium [3,4,5,6]

Property	SI Units	English Units
Modulus - Room Temp	1.03 E+11 Pa	1.49 E+07 psi
Modulus - Cryo Temp	1.23 E+11 Pa	1.79 E+07 psi
Poisson's Ratio	0.38	
Density	8.58E-03 g/mm^3	0.31 lb/in^3
Yield - RT	4.83 E+07 Pa	7.0 ksi
Yield - Cryo	5.77 E+08 Pa	83.7 ksi

Table 2: Material Properties of Titanium [7]

Property	SI Units	English Units
Modulus - Room Temp	1.02 E+11 Pa	1.48 E+07 psi
Modulus - Cryo Temp	1.25 E+11 Pa	1.81 E+07 psi
Poisson's Ratio - RT	0.338	
Poisson's Ratio - Cryo	0.305	
Density	4.51E-03 g/mm^3	0.163 lb/in^3

In the absence of data on the cryogenic properties of niobium-titanium, an assumption was made that the modulus would follow the same trend as niobium and titanium and increase by about 21% over the room temperature modulus.

Table 3: Material Properties of Niobium-Titanium

Property	SI Units	English Units
Modulus - Room Temp	7.31 E+10 Pa	1.06 E+07 psi
Modulus - Cryo Temp	8.83 E+10 Pa	1.28 E+07 psi
Poisson's Ratio	0.38	
Density	6.36E-03 g/mm^3	0.23 lb/in^3

Boundary Conditions

For the cold cavity, a 2 mm outwards deflection was applied to one of the dished heads on the cavity model while the other was held fixed, representing the maximum displacement during cavity tuning. In addition, a 4-atmosphere pressure load, the maximum failure load the cavity could experience, was applied to the outside of the cavity. (The operational pressure load is actually much lower, only 0.034 atmospheres.)

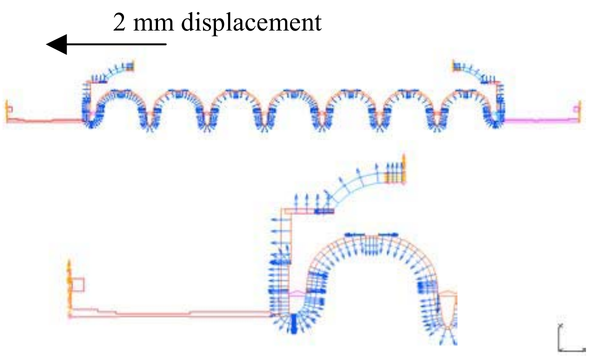

Figure 2: Loads on cold cavity

For the warm cavity, the primary concern was stress and plastic deformation from alignment, which might cause distortions in the field. The half model shown in Figure 4 was restrained in its plane of symmetry and fully fixed at the end adjacent to the cavity. The beam pipe flange was displaced vertically 1.5 mm and rotated slightly as indicated by the arrows in Figure 4. This was the largest estimated displacement of the flange during alignment.

Results

On the cold cavity, the greatest stress is at the intersection of the stiffener and the end cell, as shown in Figure 3. The yield strength of niobium under cryogenic conditions is about 84 ksi. The maximum Von Mises stresses in this area are under 20 ksi.

For the warm cavity, the maximum alignment stresses occur due to bending in the beam pipe. Since the analysis involves plastic deformation of the material, the stress-strain relationship is no longer linear. Figure 4 therefore shows the strains, which are proportional to the deflection, rather than the stresses, which are dependent on the stress-strain graph of the particular material.

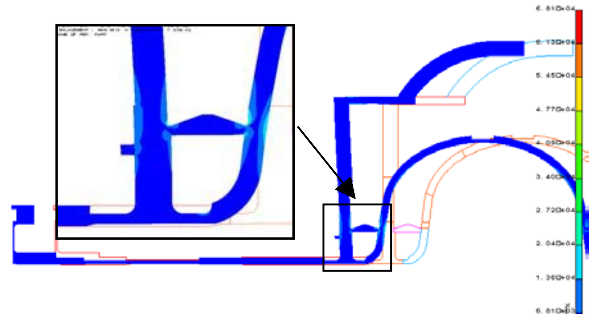

Figure 3: Low Loss – 2 mm deflection + 4 atm load

The ultimate tensile strength of niobium is much smaller warm than cold, about 20 ksi [8]. The stress-strain properties of this particular material are still being investigated. Graphs of typical niobium properties show that, for the worst-case material located, failure (i. e., ultimate tensile strength) would occur at 0.026 in/in of strain. With the given deflections, the maximum Von Mises strains in the cavity beam pipe are about 0.007 in/in.

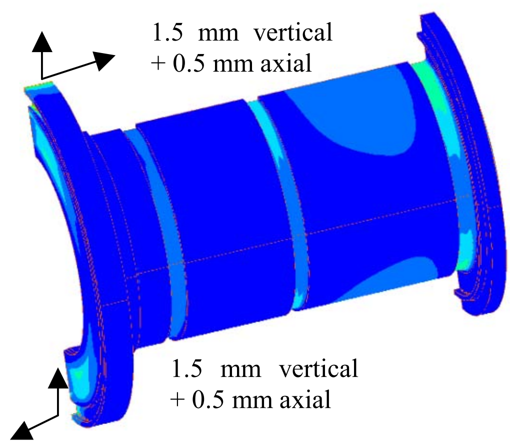

Figure 4: Alignment strains

NORMAL MODES ANALYSIS

The natural frequencies of the cavities are of interest as any external vibrations which operate at the same frequencies as the natural frequencies could induce system resonance, an undesirable condition.

Model Description

Both the high gradient and low loss cavities consist of seven cells with stiffeners between them. Additional stiffeners connect the end cells to the end dishes on each end. At both the axis and equator of each cell, weld preps result in somewhat thinner material, and this was included in the model.

A full three-dimensional model of the cavities only (without beam pipes) was meshed with parabolic shell elements. Elements shown in green are niobium and elements in red are the niobium-titanium end dishes.

The material properties used are shown in Tables 1 and 3, above.

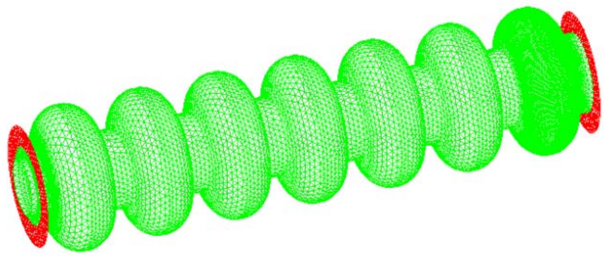

Figure 5: Shell mesh on high gradient cavity

Boundary Conditions

The stiffnesses of both the high gradient and low loss cavities were determined, using both room temperature and cryogenic material properties, to verify that these correlate with the natural frequencies. A nominal load of 100 lb was applied to one end of the cavities and the other was held fixed to determine the resulting deflection. The spring constant was calculated from this.

The fundamental frequencies of the cavities were then determined with both ends fully fixed.

Results

The cavity stiffnesses are more strongly influenced by the temperature of the cavities than by the difference in shape between the high gradient and low loss cavities, as shown in Table 4.

Table 4: Cavity Spring Constants (lb/in)

	Room Temp.	Cryogenic
High Gradient	32,400	38,900
Low Loss	32,500	39,000

The stiffnesses are also largely driven by the location of the stiffeners. For comparison, at room temperature the spring constant of a low loss cavity with no stiffeners is 8,000 lb/in and of the high gradient cavity with no stiffeners is about 17,000 lb/in. The addition of stiffeners increases the spring constants of both cavity designs several times, to about the same value.

The fundamental frequencies of the cavities are shown in Table 5. The second and third bending modes are significantly higher, as expected; for a beam, the natural frequency of the second bending mode is nearly three times higher than the first mode and the third mode is about five times higher. These are shown in Table 6.

Table 5: Cavity Frequencies, First Mode (Hz)

	Room Temp.	Cryogenic
High Gradient	114	125
Low Loss	112	123

In addition, an axial mode exists between the second and third bending modes.

Table 6: High Gradient Cavity Frequencies (Hz)

	Second Mode	Third Mode
Room Temperature	285	494
Cryogenic	312	541

For comparison, hand calculations (assuming the cavity can be treated like a beam) for the high gradient cavity at room temperature give the first three bending modes as 99, 270, and 530 Hz.

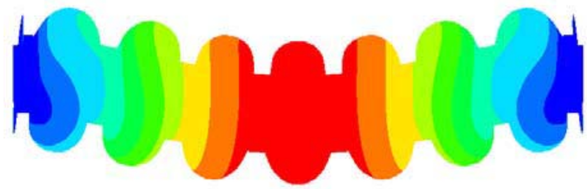

Figure 6: Fundamental mode of high gradient cavity

CONCLUSIONS

The current cavity design meets stress and frequency requirements, and manufacturing of the prototypes is underway.

Efforts to verify these analyses experimentally are ongoing. Tests on other cavities suggest that alignment within these limits will not damage the cavities and has a minimal effect on field flatness. Tests of the cavity stiffnesses and natural frequencies are currently being performed on a prototype high gradient cavity, with similar tests planned for the low loss cavities in the future.

Plans for future analyses include a study of the effects of Lorentz force detuning.

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