OPTIMIZATION OF WALL THICKNESS OF SUPERCONDUCTING 700 MHZ BULK NIOBIUM AND NIOBIUM COATED OFHC CAVITIES BY THERMAL/STRUCTURAL ANALYSIS

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Abstract

A prototype single cell superconducting elliptical cavity of β = 0.42, 700 MHz has been designed for high current proton accelerator. A detailed thermal and structural analysis is carried out on bulk Niobium and Niobium coated Copper cavities using the code COSMOS. The thermal load is coupled with the inward Liquid He pressure saturated at 1 atm. at the outer surface of the cavity. With these loads the final structural analysis of the cavity with different wall thickness has been carried out. Finally the shift in the resonance frequency due to the structure deformation is calculated using CST MICROWAVE STUDIO/ SUPERFISH code. A conical stiffener has been incorporated and analyzed with respect to the different positions at the cavity wall to see its effect on the frequency shift and on the effective stress value.

INTRODUCTION

A prototype single cell Superconducting elliptical cavity has been designed [1] to test the suitability of the cavity for high intensity proton acceleration. The 2-D cavity shape with origin at the center of the cavity is shown in Fig-1. To operate it at low temperature, the cavities are cooled down from 300 K to 4.2 K in a liquid He bath. In order to predict the RF properties and the Thermal\Structural effect [2] a two phase analysis is required. An earlier analysis has been done for CESR-type 500 MHz cavity [3] for high β structures. In this paper we have reported the Thermal\Structural effect and the RF properties of low β structures for different thicknesses of bulk Nb and Nb coated Copper cavities. All the analysis has been done using COSMOS [4], SUPERFISH [5] and CST MICROWAVE STUDIO [6]. First of all the deformation and the stress value has been computed and then the deformed geometry was transformed to SUPERFISH and CST MICROWAVE STUDIO for the calculation of RF properties.

MODELLING OF THE CAVITY

A 45° section of the cavity including the beam tube has been modeled and shown in Fig-2. This model has been analyzed for thermal and structural behavior of niobium (Nb) coated copper (Cu) and bulk niobium cavities. The material properties used for both the structure are listed in Table-1. A nonlinear variation of thermal conductivity and specific heat has been taken into account for both the types of cavities. The variation of thermal conductivity and the specific heat [7] with temperature for Nb coated Cu cavity is shown in Table-2.But for the bulk Nb cavity

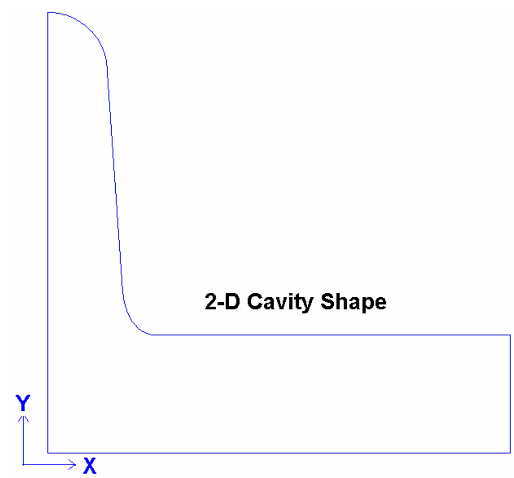

Figure 1

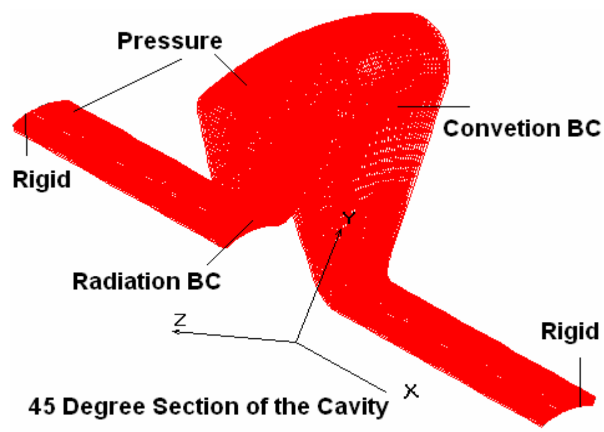

Fig 2: Model of the cavity with the general boundary conditions.

Table-1

Material Properties	Nb coated Cu cavity	Bulk Nb cavity
Young's Modulus (GPa)	110	125
Poisson Ratio	0.37	0.38
Coeff of thermal Expansion (m/K)	2.4E-5	4.9E-6
Density (kg/m^3)	8900	8570

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Table-2

Temp. K	K (W/m-K)	Temp. K	Cp J/kg-K
4	275	4	0.091
10	600	10	0.86
25	1200	20	7.7
30	1200	50	99
40	1000	70	173
60	633	90	232
90	475	120	288
130	425	180	346
200	400	240	371
300	400	300	386

the thermal conductivity of Nb (RRR250) as a function of temperature can be written as [8],

$$K_{Nb}(T) = 261.92 - 183.72T + 39.9T^2 - 1.794T^3 \quad (1)$$

and the variation of specific heat with temperature for Nb [7] is listed in Table-3. The cavity is cooled down from 300K to 4.2K inside the liquid helium bath at 4.2K. The liquid helium bath is saturated at 1 atm. Pressure. So there is an inward pressure of 101.33 kN/m^2 normal to the cavity outer surface. The resultant deformation and the stress analysis has been done subject to the proper boundary conditions at the symmetry planes and at the end of the beam tubes. In the whole analysis process the ends of the beam tubes are kept constant although in the actual design bellows will be connected at the ends of the beam tubes.

Table-3

Temp. (K)	Cp (J/kg-K)
4	0.27
7	1.5
9	3.2
10	2.2
50	99
70	152
90	189
160	243
240	261
300	268

THERMAL/STRUCTURAL RESULTS

Thermal/structural results include the helium pressure and the thermal load due to the cooling down of the cavity from 300 K to 4.2 K. Structural deformations was determined for different wall thicknesses of 3, 4, and 5 mm respectively. Structural deformation for 5mm thick Nb coated Cu and bulk Nb cavities is shown in Fig-3. Fig-4 shows the contour plot of Von-Mises stress for both the types of cavity of wall thickness 5mm. A typical plot for bulk Nb cavity of 5mm thickness is shown in Fig-5. A comparative study of both the types of cavity from the point of view of maximum deformations in radial and axial directions and the maximum effective stresses is represented in Table- 4. The table shows a better performance of the bulk Nb cavities compare to the Nb coated copper cavities. The maximum Von-Mises stresses for all the three thicknesses of both the types of cavities are well below the maximum yielding stress at 4.2K. The point of maximum deformation and the maximum stress value with respect to the axial distance happens to occur just below the intersection point of the cavity wall and the iris ellipse. So from the stress point of view all the thicknesses analyzed are suitable, but from the RF characteristics shown in the next section we will find that only 5mm thick cavity shows almost same behavior as that of the designed cavity at room temperature.

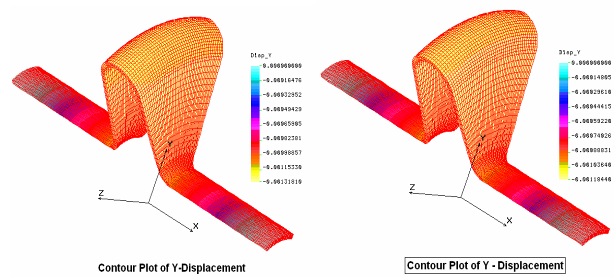

Fig. 3: Typical structural deformation for 5mm thick Nb coated Cu and bulk Nb cavities.

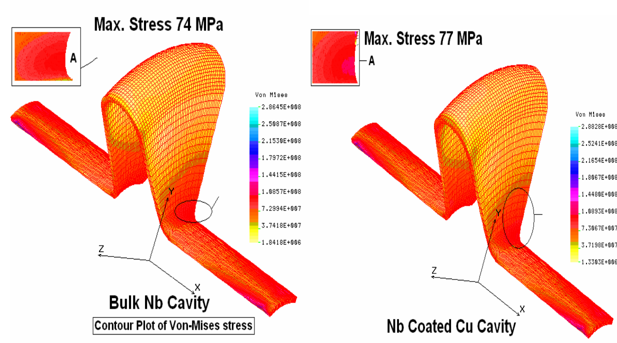

Fig. 4: Contour Plot of Von-Mises Stress.

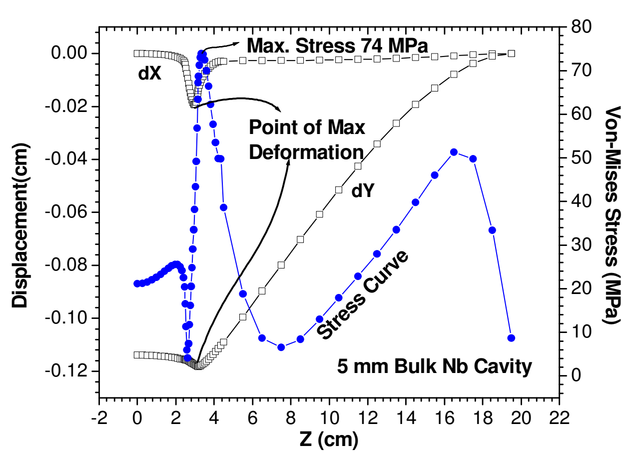

Fig. 5: Plot of Deformation and Von-Mises Stress Vs Axial Distance.

Table - 4

Parameters		Nb Coated Cu Cavity	Bulk Nb Cavity
Yielding Stress MPa		261-441	700MPa
Max Von-Mises Stress MPa	3mm	106	104
	4mm	91	88
	5mm	77	74
Y Diplacement mm	3mm	-2.850	-2.534
	4mm	-1.873	-1.676
	5mm	-1.312	-1.182
X Displacement mm	3mm	-0.418	-0.363
	4mm	-0.252	-0.216
	5mm	-0.156	-0.141

RF PROPERTIES

The RF properties of the deformed models have been calculated using SUPERFISH and CST-Microwave Studio. Due to He pressure load and the thermal load cavity will shrink which in turn increses the resonant frequency of TM_{010} mode. Some of the important cavity RF parameters under the combined load effect are listed in Table-5. The results in Table-5 clearly indicate that the RF properties of 5mm thick deformed cavity have good compatibility with the undeformed cavity irrespective of the material of the cavity. Final optimized cavity wall thickness is 5mm. It provides adequate structural stiffness and the final frequency shift is within the band of 1.602-1.374 MHz.

CAVITY MODEL WITH STIFFNER AND ITS EFFECT

A conical stiffener has been incorporated and analyzed with respect to the different positions at the cavity wall to see its effect on the frequency shift and on the effective stress value. It has been found that at the position of (Y = 2.83962 cm, X = 11.801 cm), the resonant frequency shift is minimum. Two clear holes of diameter 1cm are being incorporated with the azimuthal repetition at every 90 degree rotation. These arrangements are made in order to have homogeneous cooling effect in the entire cavity system. Computed resonance frequency shifts for 5mm thick cavities are 79 and 77 kHz. The maximum stress value is further reduced to 62 MPa, which provides additional structural stiffness. The typical plot of deformation and the stress value with respect to axial distance for 5mm thick bulk Nb cavity with stiffener is shown in Fig-6. The BW of the loaded cavity with 20 mA beam current is about 504 Hz. In order to reduce the frequency shift further and bring it at acceptable level a frequency tuner is necessary. Further studies with the tuner are on the way.

CONCLUSIONS

The two phase analysis i.e. Thermal\Structural and RF properties of β = 0.42 model cavity show the effects of cooling down under the liquid He pressure for different

Table-5

*f_0 (resonant frequency), T (transit time factor), B_{pk}/B_0 (mT/ (MV/m))

Thickness (mm)		Parameters	Undeformed	deformed
3	Nb+Cu	f_0 (MHz)	700.002	705.198
		T	0.7817713	0.7818218
		E_{pk}/E_0	1.9725	2.0271
		B_{pk}/B_0	4.1528	4.2723
	Nb	f_0 (MHz)	700.002	704.646
		T	0.7817713	0.7818164
		E_{pk}/E_0	1.9725	2.0088
		B_{pk}/B_0	4.1528	4.2719
4	Nb+Cu	f_0 (MHz)	700.002	703.058
		T	0.7817713	0.7818010
		E_{pk}/E_0	1.9725	1.999
		B_{pk}/B_0	4.1528	4.2699
	Nb	f_0 (MHz)	700.002	702.695
		T	0.7817713	0.7817974
		E_{pk}/E_0	1.9725	1.9987
		B_{pk}/B_0	4.1528	4.2707
5	Nb+Cu	f_0 (MHz)	700.002	701.604
		T	0.7817713	0.7817868
		E_{pk}/E_0	1.9725	1.9684
		B_{pk}/B_0	4.1528	4.2633
	Nb	f_0 (MHz)	700.002	701.376
		T	0.7817713	0.7817846
		E_{pk}/E_0	1.9725	1.9645
		B_{pk}/B_0	4.1528	4.2627

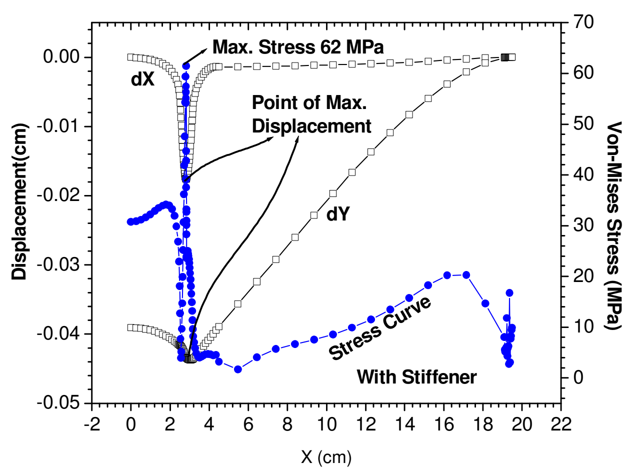

Fig. 6: Plot of Deformation and Von-Mises Stress Vs Axial Distance.

thicknesses of the cavity. The comparative study shows that the bulk Nb cavities have better performance than the Nb coated Cu cavities, from the point of view of Thermal\Structural and RF properties. For all high β cavities the optimum wall thickness is about 3 mm. But our analysis shows that for low β cavities the shift in resonance frequency is significantly high for 3mm structures. A thickness of 5mm best replicates the RF properties at 4.2 K with the original designed cavity. Also the 4mm thick cavity seems to be alright from the point of view of RF and mechanical properties. Incorporation of stiffener shows that the frequency shift comes down to few tens of KHz. In the above analysis the frequency fluctuation has been calculated taking into account the effect of cold atmosphere and the helium pressure loading. Although the other factors like helium fluctuation, Lorentz force detuning may cause significant frequency fluctuation. Detuning due to other factors will be taken care of by a suitably designed tuner. The study for the tuner is on the way.

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