MECHANICAL STUDY OF SUPERCONDUCTING PARALLEL-BAR DEFLECTING/CRABBING CAVITIES*

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Abstract

The superconducting parallel-bar deflecting/crabbing cavity [1] has improved properties compared to conventional cavity structures. It is currently being considered for a number of applications. The mechanical design analysis is performed on two designs (Figure 1) of the 499 MHz parallel-bar deflecting cavity for the Jefferson Lab 12 GeV upgrade. The main purpose of the mechanical study is to examine the structural stability of the cavities under the operating conditions in the accelerators. The study results may suggest the need for additional structural strengthening. Also the study results will help to develop a concept of the tuning method. If the cavity is to be installed in the accelerator it should satisfy certain design parameters due to the safety requirements (for example, pressure system requirements) which are much more severe than the actual operating condition.

INTRODUCTION

The current 6 GeV Jefferson Lab electron accelerator has a capability to simultaneously separate the beam to the three experimental halls. The current separator cavities are operated at room temperature. In order to preserve this capability after the 12 GeV upgrade, a new separator design is needed which presents the opportunity for a new idea to be considered for implementation. The 499 MHz superconducting parallel bar deflecting cavity is a perfect candidate. To prove the design concept a prototype will be built and tested. The test results will determine the new separator cavity type either the superconducting or the room temperature cavity.

The superconducting cylindrical parallel bar cavity is approximately 50cm long and 25cm in diameter.

CAVITY DESIGN

The shape of the cavity has been optimized in an RF study [2,3]. Over the RF cavity design (vacuum volume) shells of various thicknesses were created. The shell represents a cavity fabricated by a stamping process. Machined components were also considered to see if it offers better mechanical stability. The best value fabrication method should be determined later. This study will present mainly the cylindrical outer conductor with trapezoidal shaped bars. Table 1 shows the parameters of the cavity.

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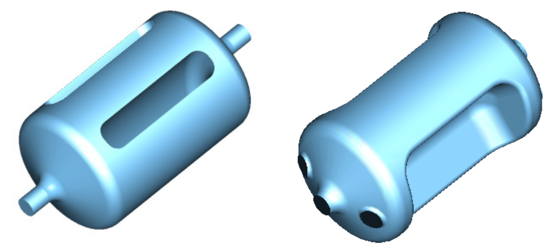

Figure 1: Cylindrical parallel bar cavity designs [2].

Table 1: Parameters-Cavity with trapezoidal bars [3]

Frequency of π mode	499.0	MHz
Cavity length	440.0	mm
Cavity diameter	241.9	mm
Aperture diameter	40.0	mm
V_T per cavity	3	MV
E_P/E_T	2.96	
B_P/E_T	4.49	mT/(MV/m)
$[R/Q]_T$	982.2	Ω
Geometrical factor	105.6	Ω
Power with beam	~0.5	kW
Power without beam	<10	W

The internal surfaces of the cavity directly affect the electromagnetic behaviour. The field sensitive areas were identified in the RF study [3] as shown in Figure 2 and 3.

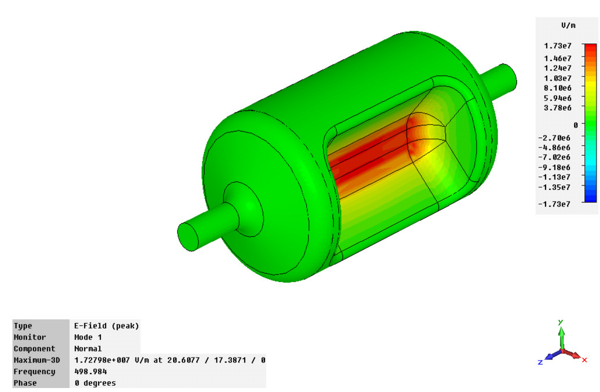

Figure 2: Surface electric field.

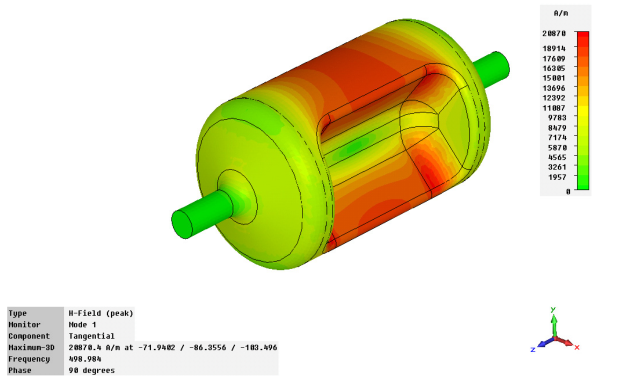

Figure 3: Surface magnetic field.

STATIC STRUCTURAL STUDY

The cavity will be subjected to the following load conditions.

- Testing condition – 1atm external pressure at room temperature during the leak check and cavity test.
- Safety requirement – 2.2 atm external pressure at room temperature governed by Jefferson Lab cryogenic system safety.
- Operating condition – 1.1 atm external pressure and tuning force at 4K during the normal accelerator operation. At 2K the external pressure decreases to 0.03 atm.

  Also a cryomodule specific upset condition exists. This study will follow Jefferson Lab cryomodule upset condition; 5 atm at 2K.

A production cavity must not yield or rupture under the three load conditions.

The stress and deformation analyses were performed using the commercial software ANSYS. Table 2 shows the material properties used in the study.

Table 2: Material Properties of Niobium [4]

Property	SI Units	English Units
Density	8580 kg/m3	0.31 lbm/in3
Poisson's ratio	0.38	0.38
Young's modulus at RT	8.27×10^{10} Pa	1.20×10^{7} psi
Young's modulus at 4K	1.23×10^{11} Pa	1.79×10^{7} psi
Yield strength at RT	65 MPa	9460 psi
Yield strength at 4K	577 MPa	83700 psi

Testing Condition

The cavity was reduced to a one-eighth model taking advantage of symmetries. The ANSYS default mesh with increased relevance was used. The model was constrained as a freestanding state. Then the atmospheric external pressure was applied to simulate a vacuum load.

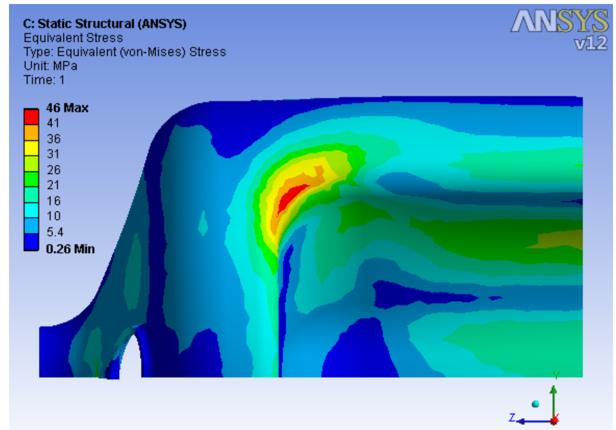

Figure 4: Von Mises stress distribution (3mm thick).

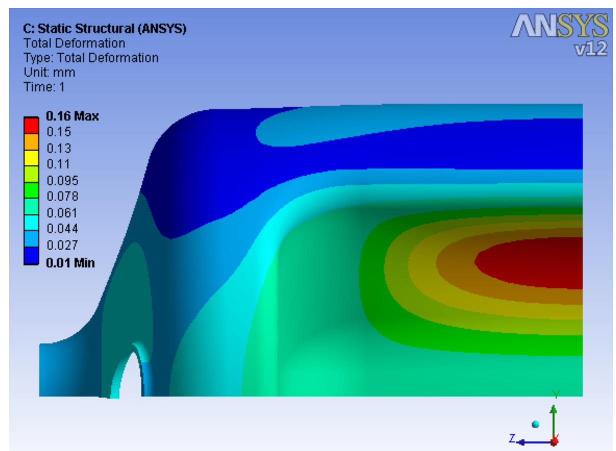

Figure 5: Total deformation (3mm thick).

The uniform 3mm thick cavity shows the maximum Von Mises stress 46 MPa (Figure 4) and maximum deformation 0.16 mm (Figure 5). The figure 6 shows the deformation under a vacuum load affecting the beam aperture. The beam aperture of the cavity is 40mm wide. The deformation of the bar surfaces (0.065mm) decreases the aperture by 0.13mm across the center.

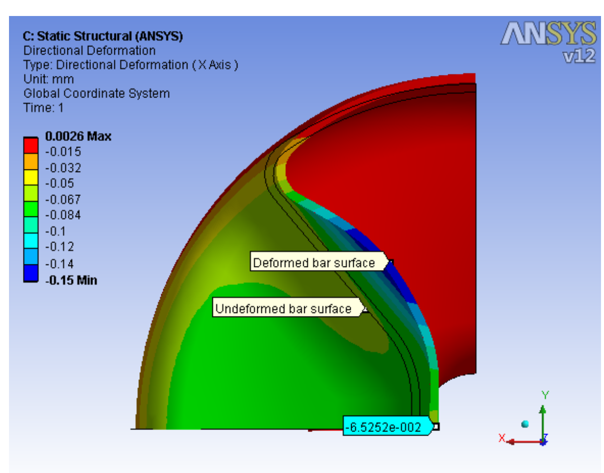

Figure 6: Directional deformation in X-axis.

The same analyses were performed with a uniform 4mm thick cavity, and a 3mm thick cavity with stiffeners (Figure 7). Table 3 is the summary of the results.

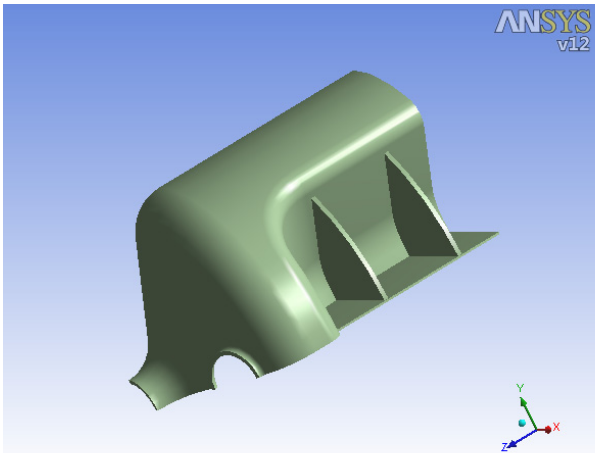

Figure 7: Added stiffeners.

Table 3: Stress and deformation comparison

Thickness	3 mm	4 mm	3 mm with stiffeners
Max stress	46 MPa	30 MPa	40 MPa
Max deformation	0.16 mm	0.085 mm	0.083 mm
Aperture closing	0.13 mm	0.10 mm	0.14 mm

A 3mm thick shell cavity, even without the stiffeners, does not exceed the yield stress under the testing conditions. But the change on the electromagnetic property due to the surface deformation should be verified.

Safety Requirement

When the 3mm thick cavity is under 2.2 atm external pressure the peak stress exceeds the yield strength at room temperature. The three cavities studied above; a uniform 3mm thickness, a uniform 4 mm thickness, and a 3mm thickness with stiffeners; would not rupture but the permanent deformation is observed. A modified production cavity design with a machined part is shown in Figure 8. The stress analysis is done with the beam pipe and the ports attached (Figure 9).

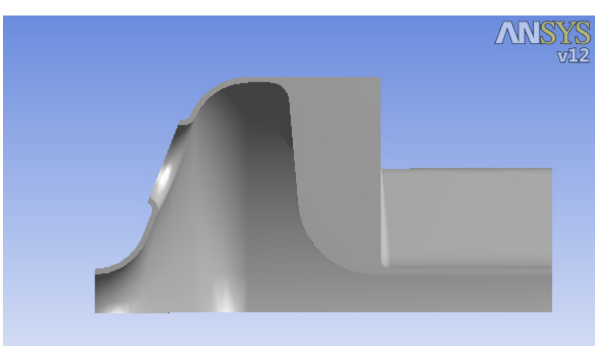

Figure 8: Production cavity design.

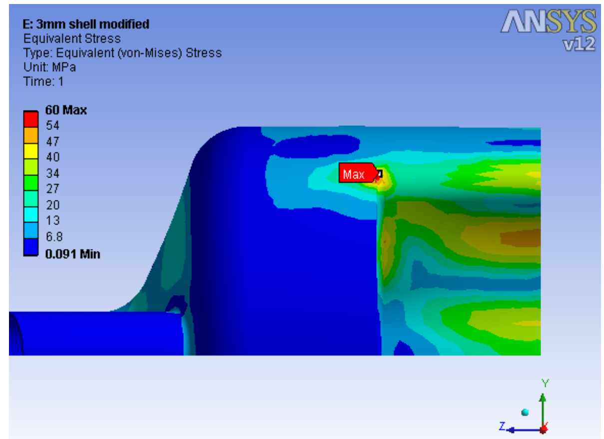

Figure 9: Von Mises stress under 2.2 atm pressure.

The peak stress of the modified design is 60 MPa (Figure 9). However, the peak stress area is localized as shown in the Figure 10. The stress throughout the cavity is under 50 MPa. An elastic deformation of 0.3 mm is observed under the safety requirement condition. The cavity can therefore recover its original geometry once the pressure is relieved.

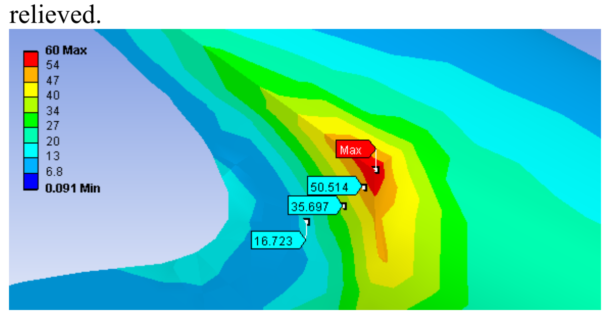

Figure 10: Cross section of local yielding area.

Operating Condition

Under operating condition the bar surface deforms a maximum 0.1mm and the maximum Von Mises stress is less than 30 MPa. The center of the bar surface, where the electric field is strong, is stable with a deformation under 0.02mm.

The peak stress under the upset conditions is far below the yield stress at 2K (Figure 11).

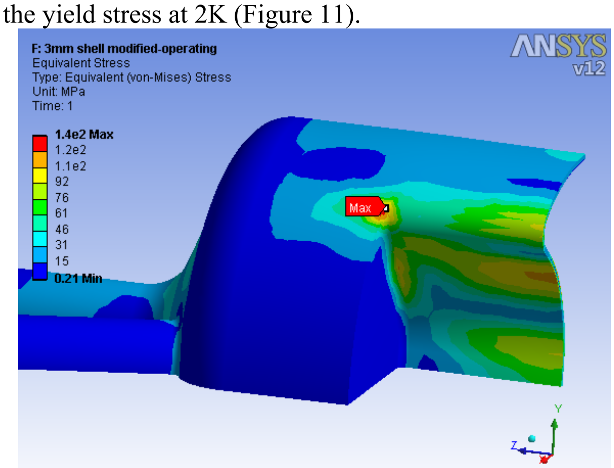

Figure 11: Peak stress 140MPa at upset condition.

For the tuning during operation, an axial load (Z direction in the model coordinate system) is desirable because this load can be applied without penetrating the helium vessel. Depending on the effectiveness of tuning by axial load radial load (Y direction) is also an option.

Under a tensile axial load the bar surfaces increase their distance from the centerline whereas the body curvature collapses toward the center. These opposing movements of the surfaces may not be effective in tuning.

The production cavity shows less surface deflection under the same load due to the stiffening effect of the added material. Tuning is most effective when either one of electric field or magnetic field sensitive surface is deformed. The behaviour of the cavity under arbitrary tuning loads is summarized in the Table 4. Figure 12 identifies the surface where the maximum deformation was measured. To see the only effect of the tuning force the external pressure was removed.

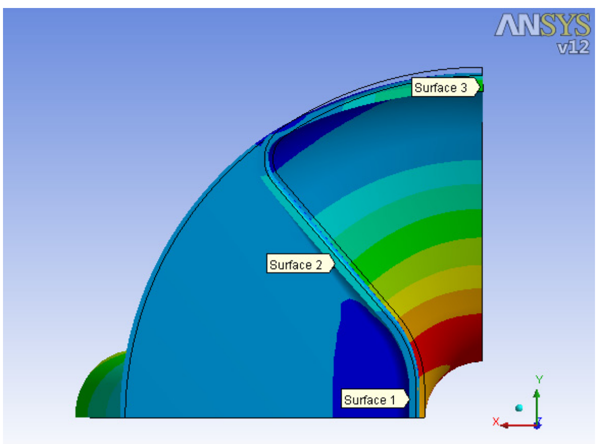

Figure 12: Field sensitive surfaces.

Table 4: The elastic deflection at tuning

Load direction	Surface 1	Surface 2	Surface 3
Axial 1335N	0.02 mm	0.03 mm	0.05 mm
Axial 2670N	0.05 mm	0.10 mm	0.06 mm
Radial 250N	0.04 mm	0.05 mm	0.18 mm
Radial 500N	0.08 mm	0.10 mm	0.37 mm

The axial load deforms the surfaces much less than the radial load. The electromagnetic study should be repeated with the deformed surface states to find the tuning range. At first glance the radial force provides a wider tuning range.

Ongoing Study

The thickness of the added machined section on the production cavity design will be optimized and a thermal study will be performed to verify the heat removal rate. The net effect of the surface deflection should be quantified by calculating the frequency change in the RF study. Currently the option to use the deformed geometry in the RF study is being explored.

CONCLUSION

The cylindrical parallel-bar deflecting/crabbing cavity provides an excellent mechanical stability due to its unique shape. Most previous cylindrical crabbing cavities have used 4mm thick niobium with stiffeners against a vacuum load (1 atm or 1 bar external pressure). This cavity can withstand the vacuum load without the stiffeners. However, depending on the safety requirements of application it will need some reinforcement.

When the cavity is reinforced as shown in the production design it provides advantages in performance and fabrication. The surface deformation due to the external pressure is decreased which results in less frequency shift. Machining of the end sections of the cavity simplifies the fabrication process.

The mechanical study showed that some components; end plates, main center body, and beam pipes, remain stable under all conditions considered. They are the first parts to be built while further analyses are performed.

To ensure the robustness of the fabrication process it is planned to build a full scale aluminum cavity before the niobium cavity.

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