CHARACTERIZATION AND FABRICATION OF SPOKE CAVITIES FOR HIGH-VELOCITY APPLICATIONS*

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Abstract

A 500 MHz, velocity-of-light, two-spoke cavity has been designed and optimized for possible use in a compact light source [1]. Here we present the mechanical analysis and steps taken in fabrication of this cavity at Jefferson Lab.

INTRODUCTION

The use of 4 two-spoke, velocity-of-light cavities, operating at 500 MHz is being proposed to accelerate electrons to 25 MeV to be used in a compact light source. The electromagnetic design has been completed using CST MWS©. The optimized cavity is shown in Fig. 1 and the rf properties are presented in Tab. 1. The optimization of the cavity followed the method described in [2].

Any mechanical study must take into account the intended operating conditions specific to the particular cavity. In this case, the cavity must withstand 1 atm external pressure at room temperature during the leak check and 1.4 atm during the vertical dewar testing. Additionally, the cavity must not yield or rupture under 2.2 atm external pressure during cool-down in a cryo-module. Simulation boundary conditions will be similar to those that would be realized in the case that the cavity is loaded into a machine-type cryo-module.

Table 1: 500 MHz, β_0 = 1 Cavity, RF Properties

Parameter	Value	Units
Energy Gain at β_0*	900	kV
R/Q	675	Ω
QR_s	174	Ω
$(R/Q) \cdot QR_s$	1.2×10^5	Ω^2
E_p/E_{acc}	3.7	-
B_p/E_{acc}	7.6	$\frac{\text{mT}}{\text{(MV/m)}}$
B_p/E_p	2.05	$\frac{\text{mT}}{\text{(MV/m)}}$
Energy content*	0.38	J
Power Dissipation†*	0.87	W

*At E_{acc} = 1 MV/m and reference length $3/2\beta_0\lambda$
†R_s = 125 nΩ

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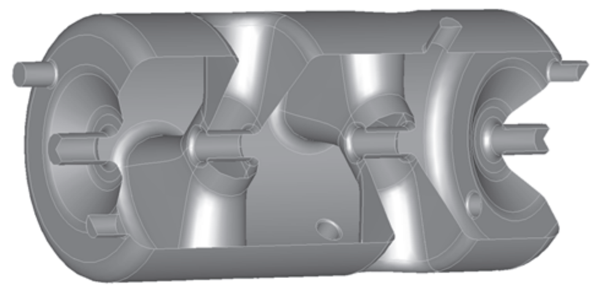


Figure 1: 500 MHz, β_0 = 1 double-spoke cavity concept.

PRESSURE SENSITIVITY

When the cavity is under vacuum, the walls will experience external pressure, from either atmospheric pressure or liquid helium, which will change the internal volume and cause stress on the cavity surface. The change in internal volume results in a frequency shift and should be accounted for in order to achieve the target frequency during cryogenic testing and operation. The stresses on the cavity surface must be analyzed to determine if the material yield strength may be exceeded, and thus compensated for.

The criteria that this analysis is intended to meet are:

- retain the design shape by identifying and strengthening the areas of the cavity which may experience plastic deformation, and
- identify what combinations of stiffening techniques can be used to minimize the change in frequency under operating conditions

The deformation and associated von-Mises stress on the cavity due to the atmospheric pressure are found using ANSYS. The cavity is intended to be mounted in a helium jacket and cryo-module, which gives us an idea of the boundary conditions we will use throughout the simulation. The bare, 3 mm thick quarter-cavity with 4 mm thick spokes, is fixed at the beam pipes. Any further analysis will be done on a cavity that has been sufficiently stiffened/supported to withstand the maximum 2.2 atm at room temperature. The pressure sensitivity, Lorentz force detuning, and modal analysis studies will then be done on those cavities at 4 K operating conditions.

The material properties used are [3]

- Nb density = 8580 kg/m^3

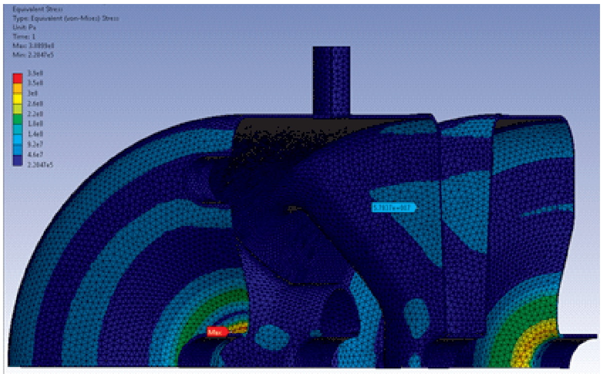


Figure 2: von-Mises stress under 2.2 atm, on the bare, 3 mm thick cavity, 4 mm spokes, with the beam pipes fixed.

- Young's modulus at room temperature: 82700 MPa
- Young's modulus at 4 K: 123000 MPa
- Poisson ration = 0.38

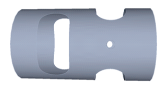
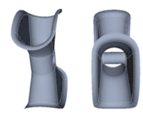
The areas that experience the greatest stress (shown in Fig. 2), for the bare cavity, are where the beam pipes meet the reentrant end caps and the spoke body. Because of this, a stiffening mechanism(s) must be imposed in those areas.

We have explored previously proposed stiffening mechanisms such as ribs [4, 5] and rings [4, 6]. At 2.2 atm, both the end caps and spokes need to be either stiffened or thickened. We have found that 4 mm thick spokes allow them to withstand this pressure, so this is the solution chosen here. A conceptual design of the cavity is shown in Fig. 3.

In order to meet the criteria previously mentioned, it is important to first understand what effect deformations of different parts of the cavity have on the frequency. To do this, the approach taken here has been to divide the cavity into the outer conductor, the end caps, and the spokes. 1 atm external pressure was then applied to each of those surfaces, individually, while leaving all other surfaces free from pressure and free to move. Because the frequency is inversely proportional to the diameter of the cavity, external pressure on the outer conductor is expected to increase the frequency. We also know that decreasing the end gap lengths decreases the frequency, so pressure applied to the end caps would be expected to decrease the frequency as well. The effect from deformation of the spokes is not as straightforward to predict, and turns out to be relatively small. Table 2 summarizes the results of this analysis.

The data given is Tab. 2 provides a starting point, but does not account for how individual areas affect each other when taken as a whole. Given that any stiffening solution must meet the first criteria above, it allows us to understand the degree of stiffening these areas should receive in order to minimize the 4 K, 1 atm vacuum load frequency shift. As Fig. 4 illustrates, varying the stiffness of the end caps, by changing the number of stiffening ribs, one can greatly reduce the frequency shift at 4 K. In Tab. 3, we show how changing the number of end cap ribs can change the frequency shift due to *only* the end caps, under 4 K conditions.

Table 2: Pressure Sensitivity by Area. A 1 atm vacuum load was applied only to each of the three areas, individually, and the frequency shift was calculated.

Area	Δf (kHz)	$\Delta f/\Delta P$ (Hz/Torr)
	14	18
	-88	-120
	-0.91	-1.2

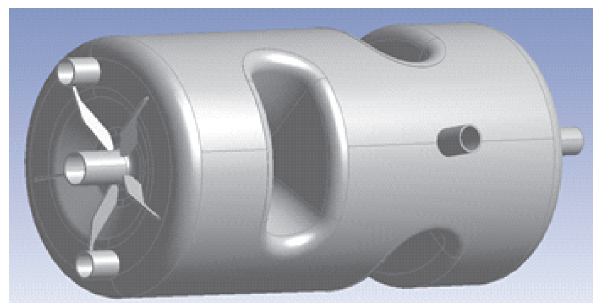


Figure 3: 3 mm cavity with 4 mm thick spokes and end cap stiffening ribs.

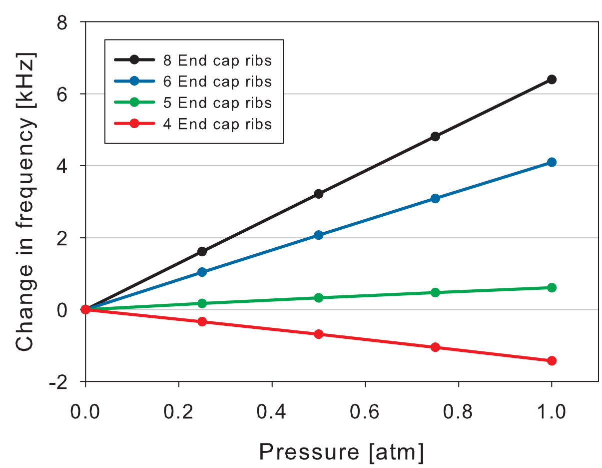


Figure 4: Change in frequency (from 500 MHz) for varying numbers of end cap stiffening ribs. Here, 1 atm external pressure was applied equally to the entire cavity.

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Table 3: Pressure Sensitivity by Number of End Cap Ribs. A 1 atm vacuum load was applied only to both end caps, and the frequency shift was calculated.

Number of ribs	Δf (kHz)	$\Delta f/\Delta P$ (Hz/Torr)
8	-3.04	-4.00
6	-5.63	-7.41
5	-8.09	-10.6
4	-11.9	-15.7

What we have attempted to show here is that stiffening a spoke cavity such that it is able to withstand 2.2 atm external pressure, is straightforward. Balancing the frequency shifts incurred by deformations from various parts of the cavity requires a judicious placement of stiffening structures, after the stress limits have been achieved. Another consideration, however, is that decreasing the number of end cap stiffening ribs does lessen the area for which the stress is distributed. So while 5 stiffening ribs on each end cap may provide a minimal frequency shift (Fig. 4, it does increase the stress on each rib.

LORENTZ FORCE DETUNING (LFD)

While these cavities are intended to operate in continuous wave (cw), we have looked at the sensitivity to LFD for other possible applications. LFD is a mechanical deformation of the cavity due to radiation pressure which results in a change in the rf eigenfrequency, and is described by

$$P = \frac{1}{4}(\mu_0 H^2 - \epsilon_0 E^2)\,, \tag{1}$$

while the resultant change in frequency will be

$$\Delta f = -k_L E_{acc}^2\,, \tag{2}$$

where k_L is Lorentz force detuning coefficient.

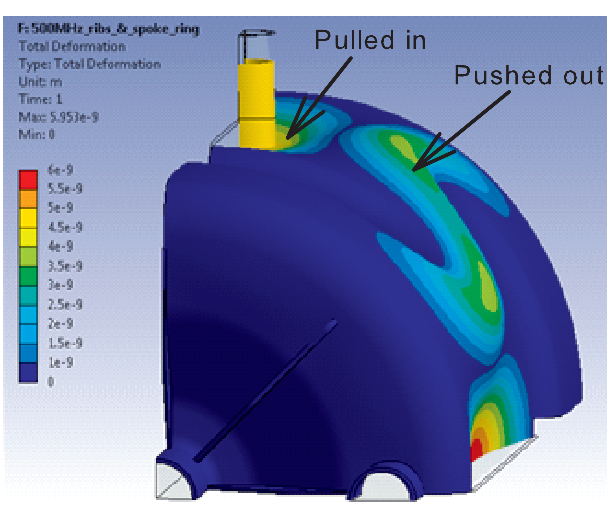

Figure 5: Cavity deformation due to LFD enhanced by a factor of 4.1 $\times 10^6$.

In cw operation, LFD will only result in a static detuning which can easily be compensated for. Figure 5 shows the cavity experiencing Lorentz pressure and it is clear where the surface magnetic and electric fields are acting. We find that, at an accelerating field of 1 MV/m and reference length (3/2)$\beta_0\lambda$, k_L = -2.6 Hz/(MV/m)^2.

MECHANICAL MODES

Mechanical vibrations from the environment can couple to the cavity, causing it to resonate. This resonant motion can cause a frequency variation of the accelerating mode, which can lead to amplitude and phase modulation of the electromagnetic field.

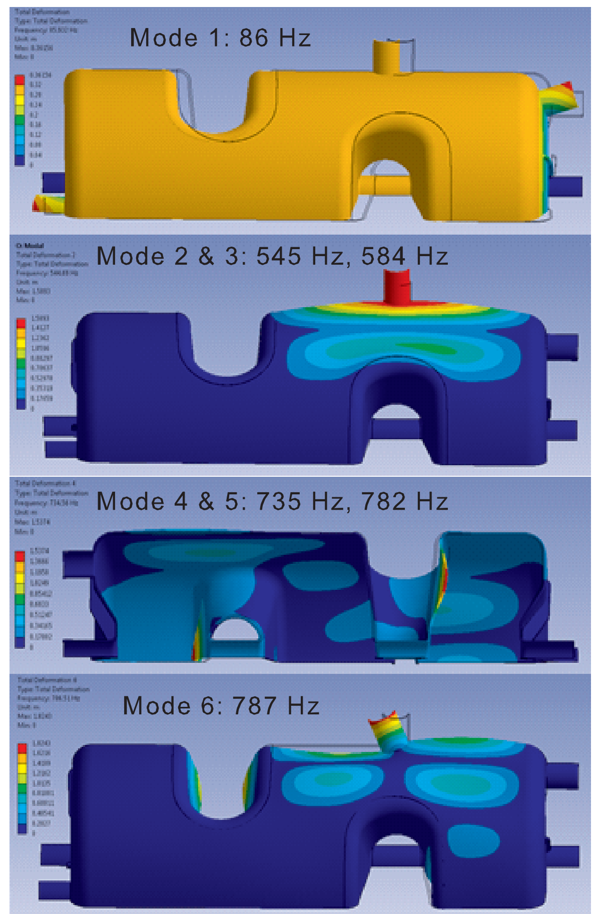

Figure 6: Cavity deformation due to the first six mechanical modes.

Figure 6 shows the deformations a cavity with 4 mm spokes and 5 end cap ribs experiences due to the first six mechanical modes. The mode spectrum will be greatly influenced by the support, stiffening, and tuning system employed. The lowest frequency mode, at 86 Hz, is a longitudinal mode where the entire cavity oscillates between the beam pipe supports. The volume (i.e. the frequency) does not change dramatically with such motion, but the frequency of this mode can be increased by additional stiffening of the end caps. For example, the mode frequency with 4 stiffening ribs on each end cap is 84 Hz, while for 8 ribs it is 94 Hz.

Modes 4 and 5 are high-frequency vibrations of the spokes, which we have seen in Tab. 2, do not dramatically impact the fundamental mode frequency of the cavity. Modes 2, 3, and 6 are high-frequency transverse oscillations of the outer conductor, and therefore could be reduced by using stiffening ribs.

FABRICATION

Presently, the fabrication process is beginning at Jefferson Lab. The parts that need to be fabricated are shown in Fig. 7. The outer conductor will be made of 4 rolled quarters, each welded together forming half of the outer cylinder. Each spoke will be formed by welding together two halves, each pressed in the same die. The spoke will then be welded into their respective cylinder halves, which will then be welded together radially in the cavity center.

Figure 8 shows a half-scale die along with a successfully formed spoke (made from AL1100).

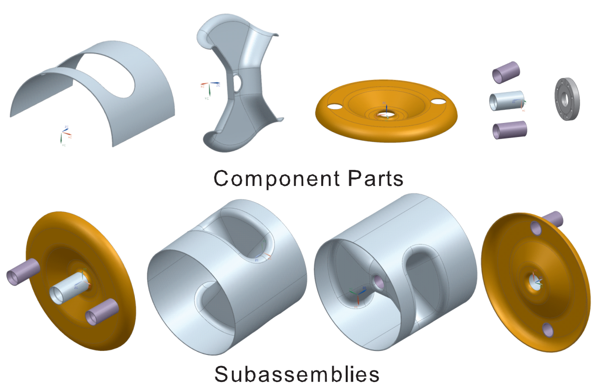

Figure 7: 500 MHz, $\beta_0 = 1$ double spoke cavity fabrication planned parts.

Figure 8: Half-scale spoke die (left) and aluminum spoke halves pressed with the die.

Currently, the full-scale spoke and end cap dies are being procured. The support structure for the post-fabrication processes, i.e. chemical processing, cleaning, and testing, has been built and beam pipe/coupler/cleaning ports are being fabricated.

CONCLUSION

The 500 MHz, $\beta_0 = 1$ double-spoke cavity fabrication is beginning at Jefferson Lab. With the mechanical analysis complete, we have identified the stiffening needs and compiled multiple options. The tuning requirements are now being evaluated, and once complete, a decision will be made on what combination of stiffening options will best meet our needs.

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