CAGE CAVITY: A LOW COST, HIGH PERFORMANCE SRF ACCELERATING STRUCTURE*

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Abstract

The Cage Cavity is a new cavity technology using tubes formed into the shape of a solid wall cavity then assembled into a closed volume. The theory is that the cage cavity will form a resonant cavity at RF frequencies below a critical frequency at which the cage structure behaves as a solid structure. The primary advantage of the cage cavity is cost—a cage cavity structure is estimated to be 1/20th the cost of a solid wall structure. Several cage cavity structures have been fabricated and measured that demonstrate good RF properties. Importantly, simulations have identified a new cage cavity configuration in which an SRF cage cavity's quality factor is >90% of a solid wall cavity. The Cage Cavity must operate in a vacuum vessel which is also an RF cavity. By choosing the cage cavity resonant frequency to be decoupled from the vessel's higher order resonances, simulations show that the cage cavity Q can be ~95% of a solid wall SRF cavity. The Cage Cavity design, fabrication costs, and high order mode behavior have a number of advantages over solid wall cavities.

INTRODUCTION

Next-generation high energy particle accelerators require RF cavities that have high accelerating gradients and cost effective. [1] Superconducting RF elliptical cavities are the preferred technology for efficient high gradient cavities [2]. SRF technology has made significant progress, especially in the last two decades. [3] However, SRF elliptical cavities are expensive and complex to fabricate and clean.

In parallel with developments of bulk niobium superconducting RF technology, there has been significant research in alternative technologies for SRF cavities. Cu cavities with Nb plating on the interior surface, lead cavities, hydroformed Nb, metal-spun Nb and "polyhedral" cavities have been evaluated, although none have exhibited properties that approach bulk Nb cavities [4-6].

DESCRIPTION OF RF-FIELD CONFINEMENT (CAGE) CAVITY

Instead of using solid Nb sheet, the RF field confinement cavity is formed using a cage constructed of tubes that are contoured to the shape of the cavity (Fig. 1) [7]. The fundamental principle is that closely spaced rods have a cut-off frequency below which RF waves, with the correct polarization, will be reflected by the rods. When the rods are shaped to form an RF resonant cavity, electromagnetic models show that the cage cavity will have properties close to the solid wall cavity, i.e. the cavity will exhibit well defined resonant frequencies and its quality factor will be close to that of a solid wall cavity.

Intuitively it is expected that the size of the gap between the tubes will determine the quality of the cage cavity. In addition, the diameter of the iris is limited by the diameter of the tubes since the tubes converge at the iris. The gap between tubes can be improved for a given tube and cavity iris diameter by interleaving a second set of tubes into the cage structure (Fig. 2).

Multi-cell structures can be fabricated by using a die to form tubes with a multi-cell design. In production, multi-cell cage cavities would cost almost the same as multiple single cell cavities. A die would form a single tube at a time to the multi-cell shell. Then the tubes would be assembled into the cavity, as illustrated in Fig. 3. The cage cavity technique could incorporate different cavity shapes into the multi-cell design, e.g. a third harmonic cavity could be integrated into the multi-cell shell by changing the tube die.

The multi-cell cage cavity design would also simplify the cryomodule design. Instead of complex He reservoirs, liquid He return lines, and comprehensive cryogenic mechanical and electrical connections, the liquid He would be run through each tube. A heat shield would be cooled by the He return, and all of the components would be in a single vacuum vessel. Even more important, the SRF cage structure could be operated using He gas at 5 to 6 K.

THEORY AND MEASUREMENTS OF COPPER CAGE CAVITY PROPERTIES

Two 40 tube copper cage cavities were fabricated in the shape of a TESLA elliptical cavity (Fig. 1). The cavities were measured using an E8362B PNA Agilent Network Analyzer. A two port technique measuring the frequency response of the S21 scattering matrix element determined the cavity resonant frequency and the cavity Q [8]. The cavities exhibited field confinement and well defined resonant modes. The two test cavities had resonant frequencies of 1,254.082 MHz and 1,255.567 MHz, compared to a calculated 1,260 MHz. The difference between calculations and measurements is 0.4%, and the difference between the two cavities is 0.12%. However, the measured quality factor was between 778 and 1586 which was lower than calculated.

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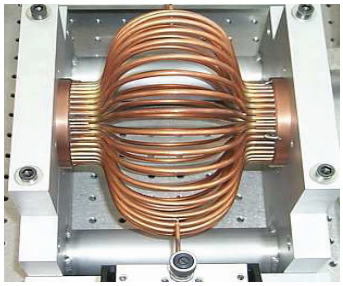

Figure 1: 40 tube copper TESLA cage cavity in a network analyzer test station.

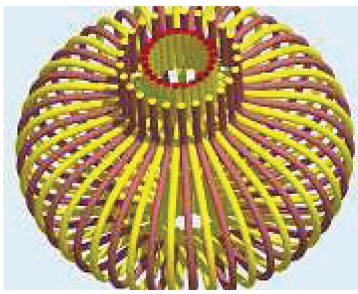

Figure 2: Model of a 72 tube interleaved TESLA cage cavity.

Figure 3: Model of a 9 cell accelerating structure with TESLA cavities.

An FEA analysis of the copper cage cavity is summarized in Table 1. The electromagnetic codes HFSS and Omega3P were used to model the fields in the cavities. Results for a standard solid wall TESLA cavity are given as a reference. The fields were calculated to produce a 20 MV/m (average) accelerating field. The fields for two cage cavities, a 44 tube and a 60 tube cavity, are compared with the solid wall cavity. In order to fabricate a 60 tube cavity, two rings of interleaved tubes are required, as shown in Fig. 2. Simulation results of the cage cavities exhibited field confinement and a fundamental frequency that was approximately the same as the solid wall cavity. Other simulated properties for the cage cavity differ from properties of the solid wall (standard) cavity, as shown in Table 1. The Q's of the 44 and 60 tube cavities are ~70% and ~90% of the solid wall copper cavity, respectively. Due to moderate field penetration of the fields into the gap between the tubes, the resonant frequency is lower. In addition to increased power loss, Bmax is higher for the cage cavity as compared to the reference. The 60 tube cavity has improved performance over the 40 tube cavity because it has more surface and smaller gaps between the tubes.

The discrepancy for the cavity quality factor between the model and measurements must be understood before the cage cavity is viewed as a viable accelerator cavity.

Intuitively the discrepancy between the measured and computed quality factor is radiation losses. Simulations of this geometry were carried out using Omega3p, a parallel finite-element eigenmode analysis code for resonant cavities developed by the Advanced Computing Department at SLAC National Accelerator Laboratory [9]. The computer simulations take advantage of the 40-fold symmetry of this cage configuration to reduce the computation time. The computational volume used is a 9 degree slice containing a single tube. The number of mesh elements is typically about 100k. The radiated power was calculated using a special module in Omega3P. By using the improved code, the calculated quality factor for a copper cage cavity in free space reduced to 2,000. Although the calculations and measurements are in reasonable agreement, a cage cavity with low quality factor is only of intellectual interest.

As the calculations for free space imply, the environment around the cavity influence the cavity quality factor. An experiment was performed in which a cage cavity is installed in a vacuum vessel. (Fig. 4) A simple plunger-type tuner was also installed in an available 4" port. The cavity Q immediately improved from 1586 to ~9,000. When the tuner's position was changed, the Q could be changed from ~200 to ~10,000. The chamber was not optimal, but the experiment illustrates a way to have a cage cavity with high quality RF properties.

Table 1: FEA Model of RF Properties for TESLA Cavity Parameters Assuming Copper Cavities and a 20 MV/m Average Accelerating Field.

	HFSS			Omega3P
	Solid wall	Cage		
Cavity	Shell	Single row	Interleaved	Single row
Tube qty/diam	n/a	44/0.2"	60/0.2"	44/0.2"
F_o (GHz)	1.29	1.26	1.28	1.26
Pwr loss (kW)	486.5	699.6	530.6	
Q	29,900	21,377	27,146	20,358
E_{max} (MV/m)	22.4	28.9	30.2	
B_{max} (mT)	57.6	116	100	

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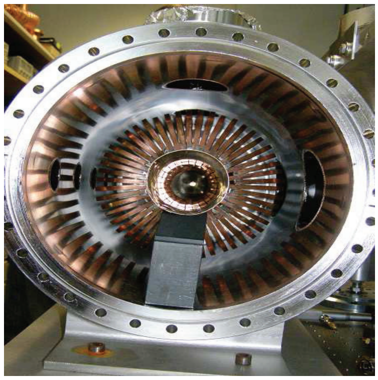


Figure 4: Copper cage cavity in a vacuum chamber.

SIMULATIONS FOR A SRF CAGE CAVITY

Generally speaking, the volume surrounding a cage cavity may take any shape and may be closed by any combination of boundary conditions. For this analysis, we restrict our attention to a one simple example: a single cell TESLA cavity enclosed within a conducting pillbox. Beam pipes are extended from the beam ports of the cavity to the faces of the pillbox. This geometry was chosen because it is straight forward to simulate while clearly demonstrating the characteristic behaviors. The exterior volume defined by this geometry is itself clearly a resonant cavity, one which can be roughly described as a length of coax capped on both ends. Its resonant frequencies can be tuned by varying the length and diameter of the pillbox. The cage cavity (along with the beam pipe extensions) is taken to be superconducting, while the outer shell is taken to be copper (Fig. 5). The fields inside the cage cavity are coupled to the fields of the exterior volume by the apertures formed by the spacing between the tubes. As a consequence, when the frequency of a resonant mode of the exterior volume lies close to the accelerating mode of the cavity, there is a strong coupling between the modes. In this circumstance, the exterior fields are similar in magnitude to the fields inside the cavity. Because of the normal conducting surfaces enclosing the exterior volume, the wall losses are then similar in magnitude to those of a normal conducting cavity. For a superconducting cage cavity, avoiding these resonances is necessary.

Figure 6 illustrates how the eigenmode distribution of the exterior volume influences the magnitude of the wall losses. When analyzing the overall efficiency of the cavity, it is necessary to separate the losses occurring on normal conducting surfaces from those occurring on superconducting surfaces. The minima are where the power in the cage cavity is fully coupled to the vessel cavity. The Q at the minima is equal to the quality factor of the vessel, which is ~20,000—the log scale makes it appear to be zero. The maxima are where the cage cavity is decoupled from the resonant modes of the vessel.

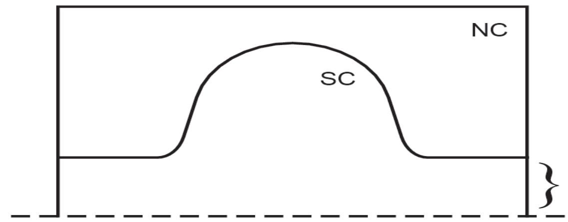


Figure 5: Cross section of FEA model of the cage cavity.

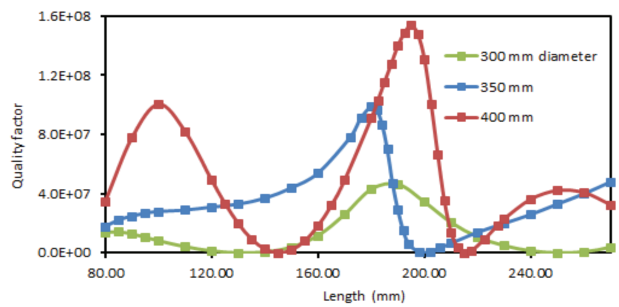
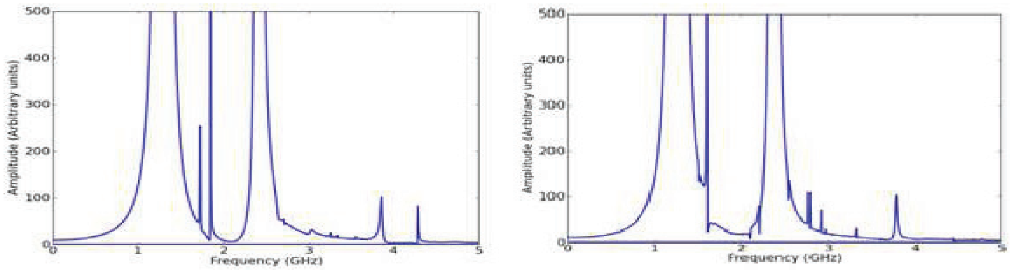


Figure 6: Plot of the cage cavity quality factor as a function of chamber length and diameter.

It is important to understand that evaluation of the cage cavity is different than the conventional understanding of solid wall cavities. The two major aspects of current SRF research are high cavity Q and high accelerating gradient. The high cavity Q is to reduce power deposited into the liquid helium bath. The power losses of the cage cavity are different. Some of the heat is deposited into the cryogenic fluid. However, the radiation losses are deposited into the vessel wall, which will also be the first heat shield in a cryomodule. The accelerating gradient will be lower than a solid wall cavity for a given geometry. The maximum B and surface E fields are higher for a cage cavity (see Table 1). Therefore, the maximum accelerating gradient is lower. Research on the high field performance of the cage cavity is being performed now.

The RF spectrum of the cage cavity at the maxima is almost the same as the spectrum for a solid wall SRF cavity (Fig. 7). The E-fields from the cage cavity in an optimized vessel are shown in Fig. 8 as a false color map of intensity. The cage cavity clearly demonstrates field confinement.

One of the advantages of the cage cavity is the ability to reduce the "fill factor" in a linac. In conventional linacs, the power coupler and the HOM dampers are installed in series with the structures in the beam line, reducing accelerating efficiency. Power coupling and HOM damping can be done coaxially for the cage structures. Figure 9 illustrates HOM damping by installing waveguide HOM dampers in the vessel wall. Most of the HOM resonances are damped. Research to design dampers to suppress the remaining resonances is in progress.



(a) Solid wall TESLA cavity (b) Cage TESLA cavity

Figure 7: Comparing calculated RF spectrum of a solid wall niobium TESLA cavity with calculated spectrum of a SRF cage cavity.

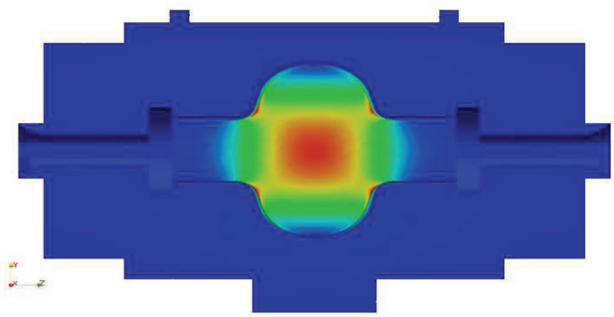


Figure 8: Intensity map of the E-field for a cage cavity in vacuum vessel that is optimized for high quality factor.

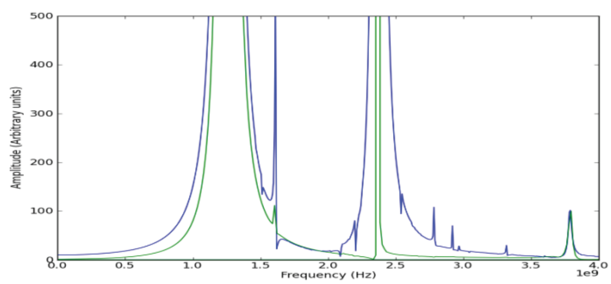


Figure 9: Comparing calculated RF spectrum for a cage cavity (blue line) and the spectrum with coaxial HOM damping (green).

CONCLUSIONS

The open structure of the cage cavity has a number of advantages over a solid wall cavity. The principal advantage is reduced fabrication cost. Prototype cage cavities were fabricated for less than $400. The cavity tubes are a base material, such as copper or aluminum. A superconducting coating is plated onto the rod which reduces the quantity of niobium required. In addition, as discussed later, the cryomodule is a vacuum chamber and the cryogenic fluid flows only through the tubes. The cryomodule module, therefore, is a simple vessel.

The cage cavity has additional advantages. A cage cavity structure is more is more insensitive to particle contamination. Since the cavity will be vented through the vacuum chamber, turbulence due to venting is distant from the cavities The RF power can be directly coupled to the structure through the cavity gap which eliminates the high power, cryogenic couplers used in existing structures. In addition, higher order mode generation and power dissipation are difficult problems in multi-cell TESLA cavities, while the cage cavities could simply transmit HOM power through the tube gaps into a power absorber. Further, due to the cage structure, an entire class of higher order modes, the TE modes, is damped significantly since the current flow of TE modes is not supported by the orientation of the cavity tubes.

The cage cavity is more flexible than a solid wall cavity, and therefore, should be more easily tuned by stretching or twisting the rods. A 1% change of a TESLA-type cage cavity volume, corresponding to approximately a 10o twist, will shift the resonant frequency by 13 MHz. The twisting force is much less than the compressive force needed for solid wall tuning of the TESLA cavities. Tuning of multi-cell cage cavities would also be simpler since a combination of stretching and twisting cells would provide significant flexibility. The cage cavity maybe more robust against microphonics than solid TESLA cavities since solid wall niobium cavities are thin and the tube construction for cage cavities is stronger with possible supports between rods for additional stiffening. A compromise would be required between tuning flexibility and its susceptibility to microphonics.

The cage cavity is a novel RF structure that has potential to be a high quality accelerating structure that significantly reduces cost, improves power coupling and HOM damping. It has additional advantages, including operation at 5 K and above, insensitivity to particle contamination, and vibration.

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