THERMAL MODELING OF HALF WAVE ACCELERATION STRUCTURES

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Abstract

Finite element techniques were used to simulate the temperature and mechanical characteristics of superconducting cavity resonators for the heavy ion accelerator at ANU. This provided accurate estimates of temperature profiles and enabled the optimization of the heat exchange interfaces between the liquid helium and the resonator substrate thus dramatically simplifying the flange coupling to the liquid helium tank. The length of the interface had significant impact on the resonator temperature, but the width or diameter had only a small effect. The optimum interface corresponds to a design in which the maximum temperature shifts from the stub to the resonator wall. Differences between interfaces had little effect on mechanical vibration frequencies.

1 INTRODUCTION

Finite element modeling is used to provide a description of the heat transfer characteristics for half wave resonator designs that have prototyped [1]. The same modeling obtains vibration responses for mechanical stability. We present some basic theory behind heat transfer and finite element modeling specifically relating to the superconducting resonators. Following a brief description of low temperature properties of materials, we show temperature profiles and the effects of design options on maximum temperature and mechanical stability. Optimal interface designs for the half wave resonators are discussed along with improvements that could be made in future analyses and suggests future work.

2 BACKGROUND

2.1 Cavities for the ANU LINAC Upgrade

The heavy ion accelerator at ANU is being upgraded continually. Recently improvements have involved the development of multi-stub superconducting resonators [2]. One of the major goals in designing these new resonators was to simplify the manufacturing process to reduce their cost by eliminating the problems with the electron beam welds. The ANU Department of Nuclear Physics has manufactured prototypes of two cavities (Figure 1) as part of a recent upgrade.

Figure 1: The prototyped resonators: Two Stub Half Wave Resonator (Left) and Three Stub HWR (right).

2.2 Computation Package

The computation package has three main parts: routines for a conduction solving, RF heating and a natural vibration frequency. The conduction routine segments the model structure and applies finite difference to them. The net heat flow into each segment is calculated by summing the heat flows from the adjacent ones, as well as external heat flow determined by the RF heating routine. The RF heating formulas incorporate the effects of anomalous skin depth in superconductors and the BCS surface impedance.

The heat exchanger routine determines the heat conducted from each segment to the liquid helium. The temperature drop across a copper substrate to helium interface is primary determined by heat flux. Above 5 mW/cm^2, bubbles start to form to remove the heat by nucleate pool boiling. Nucleate boiling persists until a peak flux of about 1 W/cm^2, above which the interface is covered with a thin film of vapor reducing further heat

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transfer. Finite element simulations can generate temperature and thermal flux profiles that can be used to make informed decisions about the optimum size of the helium heat transfer interface. Reducing the size of the helium interface may improve the mechanical stability of the resonator structure. The minimum interface may simplify the design and improve reliability of the connection between the resonator and the helium refrigeration system.

Mechanical instability is a major obstacle to resonator operation [3]. Resonant deformation is excited by background noise applied to the resonator at the frequency of one of its mechanical resonant modes. Due to the typical characteristics of background noise and the quality of the resonator normal mechanical modes, it is generally accepted that modes above 100 Hz do not cause problem [4]. Thus the design of resonators should aim for mechanical resonance frequencies as high as possible so that they do not couple with the higher intensity, lower-frequency vibrations of the background noise. General mechanical stability is also important so resonators can resist non-resonant deformation e.g. due to helium pressure changes and the electric field forces.

2.3 Low Temperature Properties of Materials

OFHC copper displays structural characteristics at low temperatures similar to those at room temperature. The change in Youngs Modulus due to temperature was modeled by:

$$E_4 = (1-3\alpha\Delta T)\, E_{273},$$

where E_4 and E_{273} are Young's Modulus at 4K and 273K respectively and α is the coefficient of thermal expansion.

2.4 The General Model

Pro/Engineer models of the resonators were created from technical drawings. The models were simplified by the elimination of joints and the holes for fasteners, i.e. the resonators were modeled as solids. For the steady state heat-transfer analysis, the finite element models had only one constraint, a fixed temperature of 4.2K, at the interface to the liquid helium. It was assumed that radiation loss from the resonator to the 80K surroundings was negligible (~ few *m*W) compared to the heat generated by the RF, 6 Watts generated on its inner surface. The distribution of this power can be approximated by the measured magnetic field using the relationship $(H/H_{max})^2 = P/P_{max}$, where H is the magnetic field and P is the RF power. The top plate, connecting the stubs to the outer can, was assumed to be fully constrained for the analysis of the mechanical resonance frequencies, To avoid the problems that symmetry can cause in analyzing natural frequency modes, both symmetric and full models were analyzed.

3 DESIGN EXAMPLES

3.1 Two-Stub Half-Wave Resonator (HWR2)

The Pro/Engineer model is shown in Figure 2. This Figure shows a quarter of the actual resonator, where two symmetric planes were used to divide the model. In Figure 2, the helium-resonator interface is shown. The segments are also shown into which the HWR2 was divided for the RF power distribution.

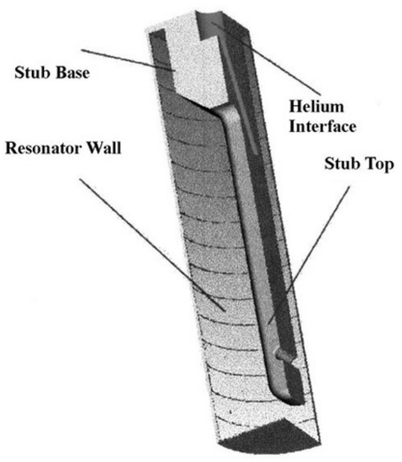

Figure 2: Finite Element Model of HWR2. Note 16 segments of the resonator wall used in calculating the power distribution.

The distribution functions used to apply the heat load on the inner surface of the HWR2 were obtained experimentally by mapping the magnetic field inside the resonator. Integration of the function fitted to these measurements over a segment, gives the proportion of the total power it gets. The stub receives the greatest proportion of the total power (54.4%), with the maximum power density occurring near the stub base.

For the HWR2, three designs were considered for the helium/resonator interface, as shown in Figure 3.

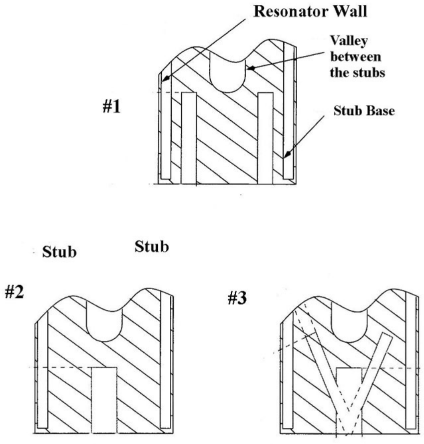

Figure 3: Cooling interface options for the HWR2.

3.2 Results of Pro/Engineer Simulations for Two-Stub Half-Wave Resonator

We focus on the primary objective of producing temperature profiles in order to optimize the helium/resonator interface. A secondary objective is to maximize the natural mechanical frequencies of the resonators and find the influence that the helium interface has on these frequencies.

Figure 4 shows how the temperature profiles respond to changes in design and size of the helium/resonator interface.

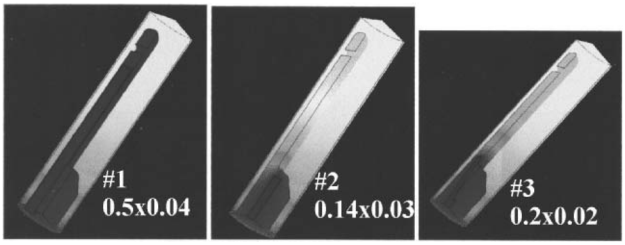

Figure 4: Temperature profiles for HWR2 (all on same color scale). From left to right: Length x Diameter in meters. The temperature increase in the light areas is 0.4K.

In option #2, the maximum stub temperature is the same as the maximum wall temperature, 4.6K, an acceptable value. Further reducing the stub maximum temperature with the more complicated design, #1 and #3, is not warranted.

Figure 5 shows the first four vibrational modes of the HWR2. The frequency of the first mechanical mode varies from approximately 117.4 Hz with virtually no cooling hole, to 105 Hz when using a large hole showing there is little variation in the frequencies of the mechanical modes between designs.

The design #2 interface, length 0.14m and diameter 0.03m, was considered to be an optimum and its temperature profile is shown in the center of Figure 4. This interface design provided a maximum temperature of 4.5K at 6W and produced a mode one frequency of 117 Hz.

3.3 Three-Stub Half-Wave Resonator (HWR3)

The three-stub resonator (HWR3) is geometrically similar to the HWR2 in that the size and the shape of the resonator walls are the same. The Pro/Engineer model for the HWR3, in Figure 6 is a quarter of the actual resonator, where the two symmetry planes were used to divide the model.

Figure 6 also highlights the helium/resonator interface and the segments into which the HWR3 was divided for the application of the heat load. The middle stub participates in oscillations with both out stubs. Thus it experiences twice the current they do. The amount of power dissipated on the resonator wall for the HWR3 is the same as that for the HWR2.

Three different designs were considered for the helium/resonator interface of the HWR3, as shown in Figure 7.

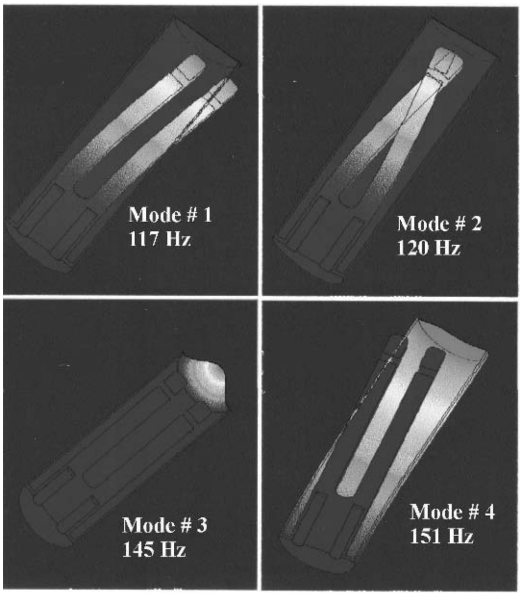

Figure 5: Mechanical modes for HWR2 (Symmetric): Design#2, length 0.14m, and diameter 0.03m.

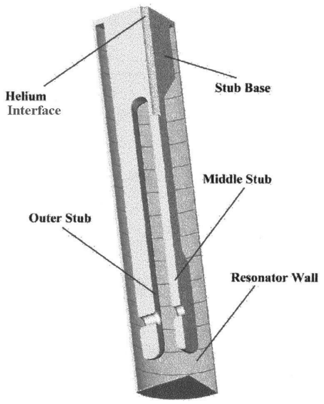

Figure 6:Finite Element Model of HWR3. Note 16 segments of the resonator wall for representation of power distribution. One quarter of the resonator is shown.

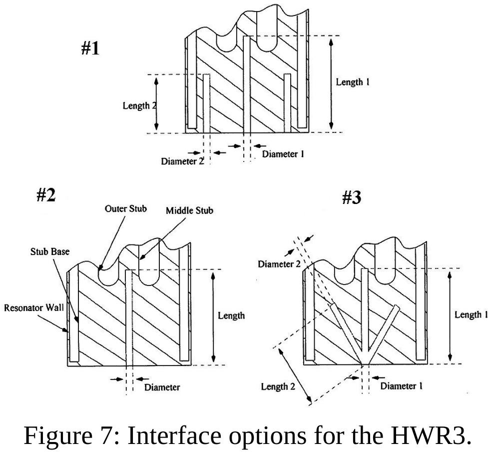

Figure 7: Interface options for the HWR3.

3.4 Results of Pro/Engineer for Three-Stub Half-Wave Resonator (HWR3)

Figure 8 illustrates the temperature profiles of the 3HWR and shows how these change as the helium/resonator interface changes in shape and size.

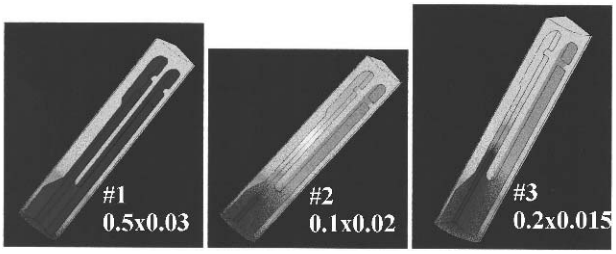

Figure 8: Range of temperature profiles for HWR3 (all on the same color scale). From left to right: (Length x Diameter in meters)

As expected, the middle stub is hotter than the outer stubs. Option #2 is the simplest and produces adequate cooling.

Figure 9 shows the first four vibrational modes of the 3HWR. The frequency of the first mode varies from approximately 68.2 Hz with virtually no cooling hole, to 60 Hz when using a large hole. There is little variation in the frequencies of the mechanical modes between the cooling designs.

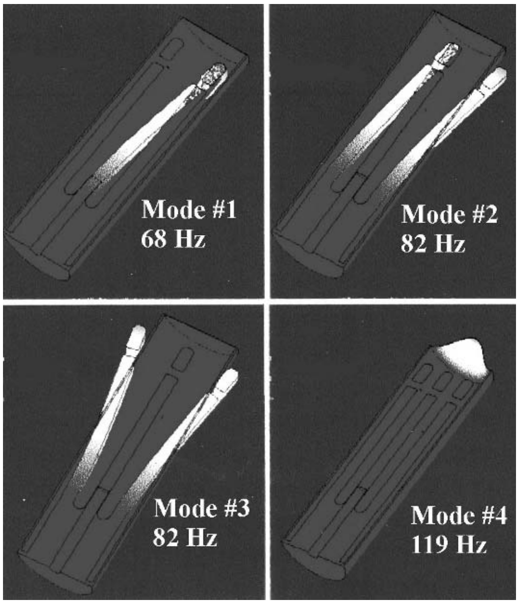

Figure 9: Mechanical modes for 3HWR (Symmetric): Design#2, Length 0.23m, and Diameter 0.015m.

A design #2 interface of length 0.23 m and diameter 0.015m was considered to be an optimum. Figure 8, #2 shows its temperature profile. This interface design gave a maximum temperature of 4.46K and produced a mode one frequency of 68 Hz.

4 DISCUSSIONS

4.1 Optimizations

For the HWR2 the range of maximum temperatures was very small, varying from 4.45K to 4.6K. The majority of this variation occurs when the length of the interface is less than 0.15m. However, once the interface is longer than 0.15m, the temperature virtually remains constant for all subsequent interface geometries. As design #1 requires two flanges (Figure 3) it was not considered further. Design #3 has interfaces, which penetrate further into the stubs, so it provides more effective cooling. However, design #2 is simpler and performs adequately, with a maximum temperature of 4.5K. Thus it was considered to be an optimum.

Design #2 was chosen for the HWR3 because it is the simplest to manufacture and is able to provide a maximum temperature approaching that of the other two designs. A flange of diameter 0.03m can be used for the HWR3 by increasing the bottom portion of the interface. This would ensure both HWR2 and HWR3 use the same size flange thus making resonator interchange easy and manufacture more economical.

4.2 Future Work

Although in all of the designs, the outer wall was the hottest, the real life situation is better because a pre-cool bar at liquid helium temperature is attached to the resonator wall near the beam holes.

To further improve the mechanical characteristics of the three-stub resonator new designs need to be considered. In general, any vibration of the inner conductor will have severe consequences on beam stability, since this motion changes the resonator geometry in the high electric field region around the beam holes. In both resonators examined, the lowest mechanical mode always involved bending of the stubs (Figures 5 and 9). The resonator with thicker stubs (HWR2) has a higher frequency lowest mode than the HWR3. Therefore, increasing the thickness of the stubs or increasing it near the shorting plate, should improve the vibration response of all the resonators. Alternatively, one might just increase the thickness of the central stub in the 3HWR.

5 REFERENCES

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