DEVELOPMENT OF A FREQUENCY MAP FOR THE WIFEL SRF GUN*

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Abstract

SRF cavity design requires the integration of several different software and analytic tools to produce a cavity which, after production and cool down to liquid helium temperatures, has the correct resonant frequency. We describe a ‘map’ which starts with a cold cavity at the correct frequency and moves back through the series of production steps producing an expected resonant frequency at each step. For example, contributions to cavity deformation from vacuum and tuner loading are modeled in ANSYS and a piecewise linear fit is produced which is re-inserted into the SUPERFISH[1] model to determine the new resonance point. We describe the steps and calculations used to develop the frequency map for the Wisconsin SRF electron gun and the specific initial cavity geometry.

INTRODUCTION

In order to use a superconducting rf cavity in a particle acceleration system, it is necessary to synchronize its resonant frequency to other accelerator systems; e.g. the photocathode drive laser. To do that the cavity itself must have its mechanical dimensions adjusted such that its resonance is an integer harmonic of all other accelerator systems. It must resonate at that exact frequency in order to accelerate particles correctly. Fortunately, modern electromagnetic design codes allow the resonant frequencies of cavities to be calculated very accurately. For superconducting cavities there are additional complications due to the mechanical deformations which occur due to evacuation and cool down to cryogenic operating temperatures. This problem is mitigated somewhat by the inclusion of an active tuner on the cavity with several bandwidths of range, but calculations of the effects on the mechanical dimensions as the cavity is taken through production and processing must be done in order to ensure the cavity has the correct frequency when completed. In addition, multiple resonance and dimensional measurements are made throughout the production process to verify the calculations, particularly on a first article.

The SRF electron gun being produced by the University of Wisconsin (UW) is a single cavity device with a unique geometry and frequency. As such, it is subject to all of the limitations stated above. It does enjoy the benefit of being a single cell, quarter wave resonator, design. This simplifies the problem since only the mechanical dimensions of a single cell need to be considered; the effect of shrinkage or stresses on adjacent cells can be ignored, and its frequency can be adjusted prior to the final cavity weld by trimming its length. However, only a single article will be produced and so the analysis to determine that length and frequency is very important. To better understand how each fabrication step effects the frequency of the cavity and to allow correction in subsequent cavities fabricated, each event in the cavity fabrication process is analyzed separately for dimensional and frequency effects. By starting with the dimensions of the final, finished cavity and applying these corrections a frequency map[2] leading from the desired finished state to the initial, prior to final weld, state can be produced. As the cavity is manufactured, actual measurement data is recorded and can be used to improve the corrections at each step, leading to a cavity with a frequency very close to the design goal.

ELECTROMAGNETIC SOLUTION AND CONVERSION TO MECHANICAL DESIGN

The initial electromagnetic solution for the UW gun was generated using Superfish[1] .

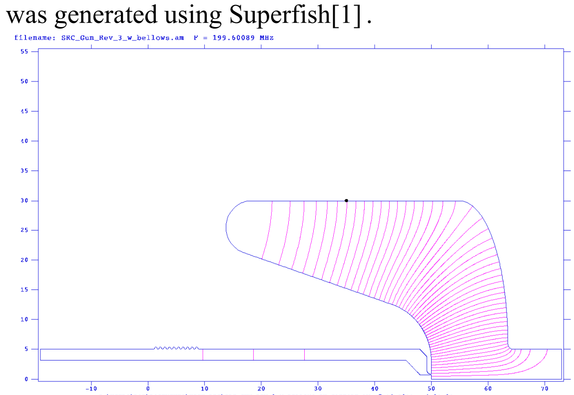

Figure 1: Electromagnetic design showing resonant frequency and final cavity dimensions.

Figure 1 shows the electric field pattern and resonant frequency of the cavity. The cavity shape was optimized to minimize the ratio of Epk / Eacc and the maximum magnetic field[3]. The mesh used was constrained to 50 microns in the cathode region to minimize errors due to the small structures and radii.

To convert the internal dimensions of an idealized cavity into a realistic mechanical structure one has to assume a particular fabrication process. Except for the cathode nose cone region that will be machined from a niobium ingot, most of the cavity will be fabricated from niobium sheet that has been rolled or deep drawn into various shapes that eventually are e-beam welded together. 4 mm thick niobium sheet is generally regarded

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as the upper limit for material availability and the deep forming process. A 3D model of the cavity with this nominal 4 mm wall thickness was generated and imported into ANSYS[4] for structural analysis. The vacuum load on the UW cavity was analyzed with a goal of making the cavity self supporting under vacuum loading. Unfortunately the resulting stress levels in the toroidal shaped cathode end of the cavity exceeded room temperature yield strength for niobium. Several modifications to this toroidal shaped region were studied in an attempt to reduce the stress levels due to the vacuum loading. Eventually a simple annular external stiffening ring was selected that kept the nominal 4 mm wall thickness but reduced stress to an acceptable level. As mentioned above, the cavity also has a mechanical tuner on it. On the UW cavity the tuner operates in tension by pulling on the anode plate in opposition to the vacuum loading with a design goal of restoring the cavity shape back to its original unloaded condition. Using the electromagnetics simulator, operation of the tuner was modeled to produce an approximate delta frequency per mm deflection. Similarly, tuner deflection based on an input force was modeled using ANSYS to yield a course frequency shift versus applied tuner force constant. Figure 2 shows the deformation of the cavity as a function

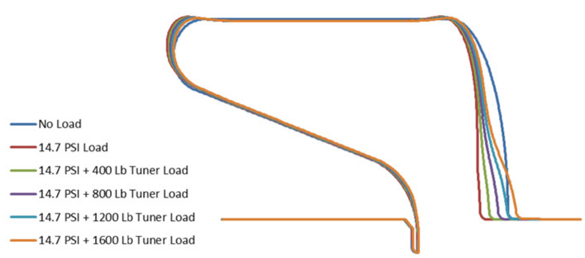

Figure 2: Cavity wall coordinates for different mechanical loads. Distortions shown are exaggerated by 100x.

of vacuum and tuner loading. This produced an initial mechanical design which corresponded in geometry to our cavity at cryogenic temperature and under vacuum. Now we needed to calculate the initial cavity dimensions.

CALCULATION LEADING TO INITIAL CAVITY SHAPE

The process steps leading from final state to initial state are laid out in Table 1.

The first step was removing the tuner force and running ANSYS to generate cavity deflections. The nodal data from ANSYS was then used to generate piecewise linear elements which could be inserted into Superfish to determine the new resonance of the cavity. The threshold for starting a new linear element was set to a 10 micron offset from the initial position. 10 microns was chosen due to the fact that the resolution of the chemical etch was only +/- 10 microns. Similarly, all linear dimensions were increased by 1.43E-3 to account for expansion as the cavity was warmed to 273 K. Again a piecewise linear fit was made to the shape with a 10 micron tolerance and Superfish was re-run to calculate a resonance frequency. Another small correction is added to account for the change in skin depth as the resistivity of the cavity changes as it is warmed.

Similarly, ANSYS is run to predict cavity deflection as the vacuum load is removed. The nodal data produce a piecewise linear fit for the deflections which is used to predict the change in resonant frequency in Superfish. Again, a small additional correction is added for the change in permittivity as the vacuum is replaced by nitrogen.

The last major change in the cavity resonance is driven by the chemical etch process. For the calculations, a uniform 150 micron was added to the inner surfaces of the cavity to account for the BCP etch. The resulting nodal data were then used to calculate a frequency change in Superfish. However, since the etch process for quarter wave structures is not strictly flow through, there is anecdotal evidence that the etch is not uniform. To evaluate the magnitude of the problem, we plan to make measurements of skin thickness on the cavity at specific points before and after the etch using an ultrasonic thickness gauge[5]. This will allow us to improve our piecewise model to include the actual etch non-uniformity in the frequency calculation and determine its effect on the final cavity frequency.

Table 1: Steps from cavity blank to final frequency

State	Freq, MHz	Δ Freq, MHz	Volume, in^3	Δ volume, in^3
Nominal, 4 K	199.58953	-	6269.213	
Remove 1600 lb preload on tuner	199.65256	0.06303	6267.753	-1.46
Warmed to 273 K	199.3704	-0.28216	6294.653	26.9
Skin depth vs temp at 200 MHz	199.3185945	-0.05180	6295.853	1.2
Remove vacuum load	199.2485945	-0.07	6300.243	4.39
Change in permitivity, fvac/fair	199.1947645	-0.05383	6300.243	0
Undo etch	199.3688075	0.174042	6282.793	-17.45
Final weld shrinkage, 0.7 mm	199.280	-0.088	6294.87	12.08

RESONANCE MEASUREMENTS AND THE FINAL WELD

Figure 3 shows the various subcomponents that make up the overall cavity. Numerous e-beam welds are required along the assembly process and each weld introduces its own shrinkage. Systematic dimensional inspection measurements will be made along the fabrication process and these measurements will be used keep track of the theoretical cavity frequency.

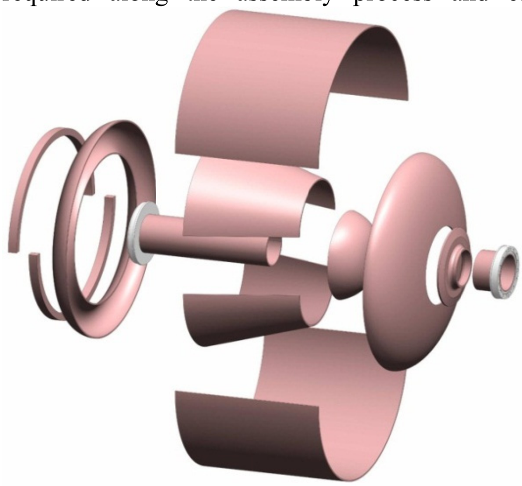

Figure 3: Exploded view showing weld joints.

To verify and instruct the accuracy of the calculations, antenna fixtures will be used to do cavity frequency measurements, Figure 4, before and after the final cut and weld. They will also be used to measure the frequency after the BCP etch, after the high pressure rinse, during and after the test of the cavity at 4 K and after the helium dewar is attached. These measurements will highlight any errors in the calculations or erroneous assumptions about the effects. By applying them to the frequency map, along with the correction for the chemical etch uniformity, a very precise prediction for the final frequency for future cavities of this geometry can be arrived at. In addition, using this data we can determine the most efficacious modification of the existing cavity to correct any defects in resonant frequency. For example, if the calculations in Table 1 are correct, the frequency can be strongly influenced by operating the helium vessel with a pressure regulator.

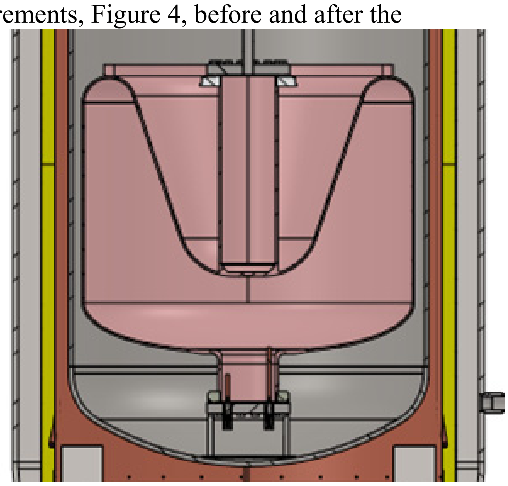

Figure 4: Cavity mounted in dewar with antennae for measuring resonant frequency.

CONCLUSIONS

The Wisconsin SRF electron gun uses a cavity which is designed to operate at a given frequency as part of a future accelerator system. In order to produce a cavity at that exact frequency, the cavity, which exists as models only in electromagnetic and mechanical simulations, must have each production step reverse engineered from the models using the finite element analysis tool and analyzed for frequency changes using the poisson solver. The largest perturbations to the cavity frequency are thermal expansion, the chemical etch and the distortion due to the vacuum load. In addition, the frequency table shows that the weld shrinkage is a very significant effect and must be taken into account by doing a frequency measurement and trim before the final fabrication weld.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J.H. Billen and L.M. Young, Proceedings of the 1993 Particle Accelerator Conference, Vol. 2 of 5, 790-792 (1993).
[2] Xiangyun Chang and Ilan Ben-Zvi, Brookhaven Technote BNL-81724-2008-IR, January 2009.
[3] R. Legg, et al., Proceedings of ERL09, p. 45, Ithaca, NY, (2009).
[4] ANSYS®, ANSYS, Inc.
[5] T. Higuchi, et al., Proceedings of the 1999 Workshop on RF Superconductivity, p 254, La Fonda Hotel, Santa Fe, New Mexico, USA.