FREQUENCY CONTROL IN THE CORNELL-ERL MAIN-LINAC CAVITY PRODUCTION *

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Abstract

Cavity fabrication can be broken down into three main stages: deep-drawing cups, welding the cups in pairs to obtain "dumbbells" and end groups, and, finally, welding the obtained components into a completed cavity. Frequency measurements and precise machining were implemented after the second stage. A custom RF fixture and data acquisition system were used for this purpose. The system comprised of a mechanical press with RF contacts, a network analyzer, a load cell and custom LabVIEW and MATLAB scripts. To extract the individual frequencies of the cups from these measurements, an algorithm was developed. Corrections for the ambient environment were also incorporated into the measurement protocol. Three 7-cell 1.3 GHz cavities were produced with high field flatness immediately after fabrication.

INTRODUCTION

Optimization of the accelerating superconducting (SC) cavity shape consists in a search of the shape in its final state. This raises the question of how the elliptic arc definition of cavities is modified during fabrication. A robust design should account for all processing procedures including etching, thermal contraction and frequency tuner preload (axial preloading is needed to minimize frequency tuner motor backlash) since we expect these steps to modify the microwave properties of our resonator. A convenient way to depict the cavity shape and technological operations changing this shape is a matrix presentation of an elliptic multicell cavity described in [1] .

Production of the first 3 SC cavities for the Cornell University Energy Recovery Linac (ERL) is complete allowing to analyze the procedure. We encountered an issue regarding frequency control of individual cells when the half-cells (or cups) are welded together to form "a dumbbell". Because of a non-ideal shape of the cups and not fully controlled shrinkage of material by welding the cups are intentionally manufactured with some extra length on the equator which should be trimmed in the following processing. We used experience in fabrication of SC cavities described in DESY and JLab publications [2, 3, 4]. Both labs used measuring fixtures with a perturbing body to identify a possible asymmetry of the dumbbell. There is no direct reference in the DESY publications how this asymmetry is used to define the individual cup frequencies, but in the

JLab publication the measured frequencies with and without perturbation were used for the definition of the π-mode frequencies of the cups. Some corrections to the formulae for calculation of these frequencies and a more detailed description of the dumbbell measurements were presented earlier [1]. Here we want to present the main points of this work and the most recent results of the frequency control in the cavity production.
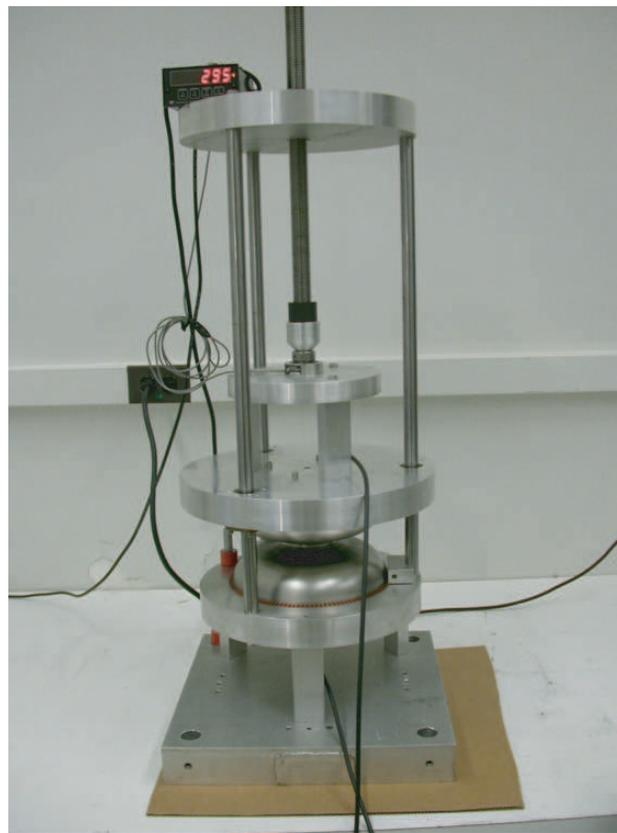
A DUMBBELL MEASURING FIXTURE

Figure 1: Dumbbell measuring fixture with a dumbbell under test, the applied force is 295 pounds.

To measure the resonant frequencies of a fabricated niobium dumbbell, a fixture with supporting hardware and software was constructed, Fig. 1. The system was inspired by the JLab system, with the most notable difference being the operating frequency (1300 MHz instead of 1500 MHz) [4]. The fixture was designed to accommodate completed end group measurements also. In the case of end groups,

no perturbation was used since the cavity was comprised of a single half-cell. Two feedthroughs with antennas were placed in the upper and lower plates, and the RF measurement was done in transmission. For the end group, one antenna was replaced by a flexible conductor such that it was easily inserted into the cavity. In each case, the antenna length was trimmed such that the cavity was heavily undercoupled with a $Q_{ext} \approx 10^6$, giving $Q_l \approx Q_0$.

The measurement system consists of a HP85047A network analyzer (NA), a RF dumbbell fixture with copper contact fingers, and a Transducer Techniques load cell with analog readout. The NA and load cell were connected to a LabVIEW program which logs the frequency (f_0), quality factor (Q_0) and applied force. Q_0 and f_0 were determined by fitting the amplitude of S_{21} to the Lorentzian function while accounting for a constant direct transmission between antennas. LabVIEW was choosen to increase the measurement accuracy while simplifying the measurement and processing procedure.

The six measured frequencies comprised the 0 and π-mode, with and without perturbation in the upper and lower half-cells. These values were written to a file and then processed using MATLAB. The script calculates the individual π-mode frequencies according to the modified formulae [1]. The program also incorporates a correction for ambient conditions: humidity, temperature and atmospheric pressure as it is described above.

The value of the frequency perturbation should be bigger than the error in measurement (10 kHz) but less than the difference between the 0 and π-mode frequencies (about 26 MHz). We have chosen our perturbation such that $\Delta f \approx 0.5$ MHz. The perturbing body is a cylinder 3.175 mm in diameter with a spherical top, and the total length of 6.5 mm. In order to guarantee reliability, the perturbation was fastened with a torque wrench to 10 inch·lb.

To obtain a reliable RF contact at the Nb/Cu joint, the fixture must compress the dumbbell between copper plates. The mechanical press comprised of linear bearings mounted on aluminum plates, sliding on case-hardened shafts. The press was manually driven by a 1-inch ACME screw. ANSYS simulations show that the force applied to the dumbbell should be kept below 350 lbs, in order to prevent inelastic deformation. Therefore, our operating pressure was 300 lbs. Elastic deformation will affect the resonant frequency of the cavity, but a linear extrapolation to zero pressure of the f_0 versus F curve found this deviation to be negligible compared to our machining tolerance. To overcome the dry-contact friction between components, a small mechanical vibrator was attached to the fixture. It was also helpful to wait a minute or two after applying the clamping force. The assembly would generally relax over the course a couple minutes, losing ∼10 lbs of force. The drive screw could be then retightened. Between cavity production, it was found that after several months the copper will corrode sufficiently to limit the Q to ∼3500. Cleanliness of the weld equator to copper plate electrical contact was achieved with a green scotch bright pad and isopropyl

alcohol to remove copper oxidation before use of the instrument for RF measurements. Once the cleaned surfaces are in contact with each other a mild twist of the part between the copper plates is done to seat everything and insure good contact between the equator and copper plate. To exclude the copper contamination of the niobium, a 30 minute nitric acid etch of the equators was performed prior electron-beam welding. This removes copper without action on niobium.

The theoretical value simulated in SLANS was about 7500 for both 0- and π-modes, given our geometry and materials. We assumed that a Q_0 greater than 5000 indicates a reliable RF contact. Using the methods outlined above, we had repeatable frequency measurements with $\sigma = 10$ kHz, regardless of cavity orientation or re-insertion.

CORRECTION FOR MEASUREMENT CONDITIONS

The dimensions of the 7-cell ERL cavity were optimized [5] taking into account different constraints for the frequency $f = 1300.000$ MHz using SLANS [6]. We have chosen a 300 kHz preloading (stretching), so the frequency before stretching should be 1299.700 MHz. If shrinkage only due to niobium thermal contraction from 293 K to 2 K is considered, the starting dimensions of the cavity should be bigger by 0.143 % [7]. The frequency before cool down should be by the same factor lower: 1297.844 MHz. This is the design frequency at room temperature ($T_0 = 293\ K$) but without regard for dielectric permittivity of air. ε of air depends on the atmospheric pressure p, humidity φ, and temperature T [8]:

$$\varepsilon = 1 + 210 \cdot 10^{-6} \frac{p}{T} + \varphi \frac{p_{sv}}{T} \left(\frac{10040}{T} - 0.30 \right) \cdot 10^{-6} \quad (1)$$

Here p - directly measured atmospheric pressure, and p_{sv} - water's vapour saturated pressure, are measured in mm Hg, T - Kelvin, φ – %. p_{sv} can be approximated [9] by:

$$\log p_{sv} = 7.45 \cdot \frac{T - 273}{T - 38.3} + 0.656, \quad (2)$$

which very well coincides with table data used in [4].

For normal conditions ($p = 760$ mm Hg, humidity = 50 %, $T = T_0$), ε of air in (1) is equal to $\varepsilon_{nc} = 1.000646$.

The frequency measured in atmosphere will differ from the calculated by SLANS:

$$f_{meas} = \frac{f_{calc}}{[1 + \alpha(T - T_0)]\sqrt{\varepsilon}}$$

where $\alpha = 7.3 \cdot 10^{-6}$ K^{-1} is the thermal expansion coefficient of niobium at room temperature.

Monitoring the environment effects became apparent during one of our sessions of measurements when a strong low front came in while we were frequency measuring and the "unfiltered" frequency changed during multiple measurements of the same part.
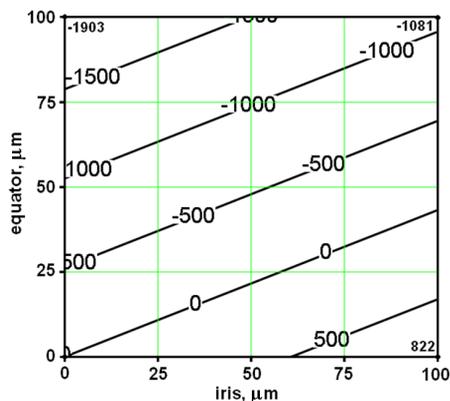
Figure 2: Frequency change (kHz) for different etching of iris and equator in the ERL cavity.

CMM MEASUREMENTS

During production of the ERL 7-cell cavities, great care was taken at all stages to maintain tight tolerances with the express purpose of preserving cavity cell shape. Each untrimmed stamped cup was measured using a coordinate measurement machine (CMM) to verify that the inside profile of the cup was correct (typical maximal deviation about 0.25 mm). After this measurement, the weld prep for each half cell iris was trimmed using a 3-axis CNC milling machine, allowing for a high degree of precision. Shrinkage from welding the iris to an adjoining iris was factored into the weld prep design to assist in preserving each half-cells shape. Following machining, all of the trimmed cups were again measured on the CMM to verify that the inside profile was still intact. After this, the half-cell cups were welded into dumbbell assemblies. Upon completion of the welding process, each dumbbell was again measured with the CMM to confirm that the weldment had not distorted. The dumbbell weldments were then measured using the RF dumbbell measurement fixture to determine each half-cells frequency. This frequency measurement determined the final length of the dumbbell.

CORRECTION FOR ETCHING

In the correction for chemical etching (BCP) mentioned above we assumed that etching is uniform on the whole cavity surface. However, because of different speed of the electrolyte flow near equator and iris, the etching speed might be different at these locations. We define the equator area as the part of the cavity surface on which $\mu_0 H^2 > \varepsilon_0 E^2$ and the iris area where this inequality is opposite. Etching in the equator area and in the iris area leads to frequency shifts of different signs, so that a small decrease of the equator etching can lead to a significant deviation from the expected value.

One can see from Fig. 2 that if etching in the equatorial area is about 70% of etching in the iris area, the frequency shift will be about a half compared to uniform etching. Our findings indicate, however, uniform etching rate.

SUMMARY AND CONCLUSION

Frequency corrections due to cooling down, preloading and atmospheric conditions are analyzed.

To find the target frequency of our measurements at normal conditions we can summarize the above mentioned results for each state of the cavity preparation (in MHz):

Vacuum, 2 K, preloaded 300 kHz (stretched)	1300.000
Without preloading (2 K)	1299.700
All the same but at 20°C (divide by 1.00143), vacuum	1297.844
In air: 20°C, 50% rel. humidity, 760 mm Hg (divide by 1.000323)	1297.425
Before BCP (1560 kHz/150 μm), target frequency	1298.985

Difference between the measured and target frequency was used to find the length to be trimmed using the "trimming parameter" (found by SLANS): $t = 128$ kHz/0.001inch (5.039 MHz/mm). Dumbbell cavities for the Cornell ERL multicell cavity were measured in a measuring fixture constructed to determine equator trimming lengths. Earlier used formulae for calculation the individual half-cell frequencies were revised and corrected. LabVIEW and MATLAB software were written for a semi-automatic measurements with a network analyzer, load cell, and RF dumbbell fixture. Our system helped to control individual cell frequencies to within narrow limits: the first three completed Cornell ERL 7-cell cavity have a field flatness better than 80 % immediately after fabrication and frequency deviation below 400 kHz that corresponds to an average deviation of less than 0.1 mm per cell.

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