# FREQUENCY MEASUREMENT AND TUNING OF A 9-CELL SUPERCONDUCTING CAVITY DEVELOPED WITH UK INDUSTRY

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## *Abstract*

As part of an STFC Innovations Partnership Scheme (IPS) grant, in support of enabling UK industry to address the large potential market for superconducting RF structures, Daresbury Laboratory and Shakespeare Engineering Ltd are collaborating to produce a 1.3 GHz 9-cell niobium cavity. This paper describes the procedures to ensure the cavity reaches the required frequency and field flatness. The frequency of each half-cell was measured using a custom measurement apparatus. Combined mechanical and RF simulations were used to compensate for cavity deformation during measurement. Results of Coordinate Measurement Machine measurements of one half-cell are presented. The same procedure will be used to trim the cells at the dumbbell stage, and the full 9-cell cavity will be tuned once welded.

## INTRODUCTION

Daresbury Laboratory has been working with Shakespeare Engineering Ltd [1] for several years to enable the full fabrication of superconducting RF cavities in the UK. Previously the collaboration, along with Jefferson Laboratory [2], produced three single-cell niobium cavities, the last of these reaching a gradient of 40 MV/m after electro-polishing and centrifugal barrel polishing [3]. The current project is part of an STFC Innovations Partnership Scheme (IPS) grant to produce a 9-cell cavity, and has already accomplished the production of a copper 2-cell prototype cavity. A 9-cell Tesla style cavity has been designed, incorporating both spun beam pipes to remove the need for a seam weld, and steps on the equator and iris surfaces to facilitate alignment [4]. The non-welded parts for the 9-cell cavity have been delivered, and quality testing of the half-cells has been performed at Daresbury Laboratory.

## HALF-CELL MEASUREMENT

### *Frequency Measurement*

18 niobium half-cells have been received from Shakespeare Engineering. These consist of 8 female half-cells (CF1-8), 8 male half-cells (CM1-8), 1 male (EM1) and 1 female (EF1) end-cell, where the sex of the cell is defined by the alignment steps at the equator, which will be added to the cell at the dumbbell trimming stage. Currently each cell has extra length at the equator which will be trimmed to correct the frequency.

In order to measure the resonant frequency of each half-cell they were clamped between two copper plates with RF fingers flexed upward by a recessed O-ring as seen in Iversen et al [5]. RF antennas were then inserted at the top and bottom and an S21 measurement performed. Figure 1 shows the experimental setup, and Figure 2 shows the RF contact area in more detail.

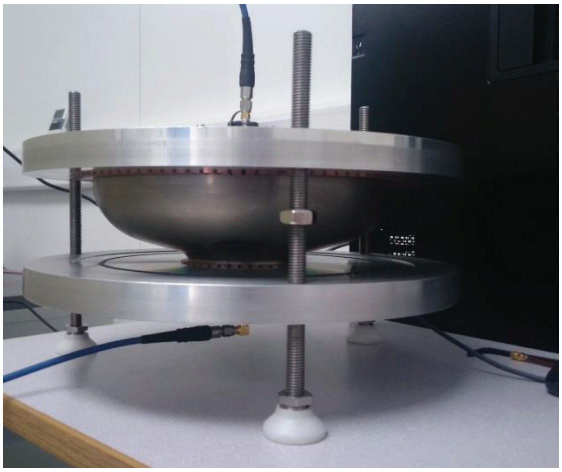

Figure 1: Photograph showing the experimental arrangement used to measure the S21 of a half-cell.

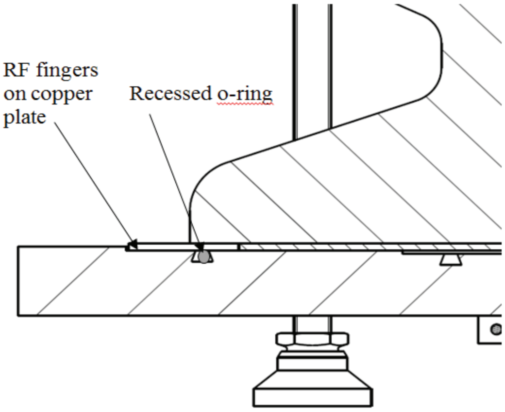

Figure 2: Detail of the RF contact area for S21 measurement.

Good RF contact, defined in this context as a bandwidth of 2 MHz or less, was achieved by the application of weight to the top of the test stand. The minimum weight possible, 3kg, was used in order to decrease deformation of the half-cell. The parallelism of the top plate was measured using dial test indicators at four points on the plate.

Exemplar S21 curves for each half-cell are shown in Figure 3, and Figure 4 shows the spread of measurements for each cell. All measurements have been corrected for ambient humidity and temperature in the test environment.

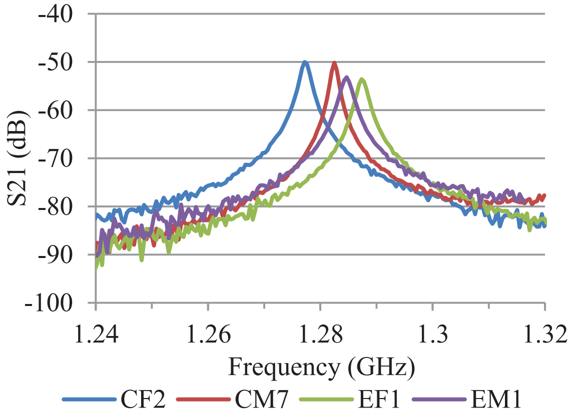

Figure 3: Example S21 measurements of each half cell.

In Figure 4 it can be seen that the frequencies of each of the four types of half-cell, shown in different colours, fall within a range of around 5 MHz, with outliers in CF4 and CM3. This indicates the good reproducibility of the manufacturing process.

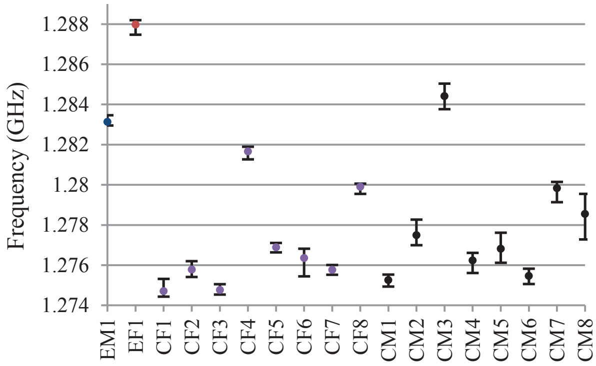

Figure 4: The frequency of each half-cell. The error bars show the variation in the 5 measurements taken for each point.

### *Comparison to Simulation*

Each cell type was simulated, including the extra length for trimming, in the Eigenmode solver of HFSS [6]. The simulated frequencies were low compared to the measured frequencies in the order of 10 MHz as shown in Table 1.

As the cell is clamped for the test, a frequency change is expected due to cell deformation. Therefore combined mechanical and electromagnetic simulations were performed in ANSYS/HFSS.

The non-deformed half-cell geometry was imported into a Static Structural module in ANSYS. The weight used to clamp the cell was applied to the equator as a ramped force. The total deformation can be seen in Figure 5.

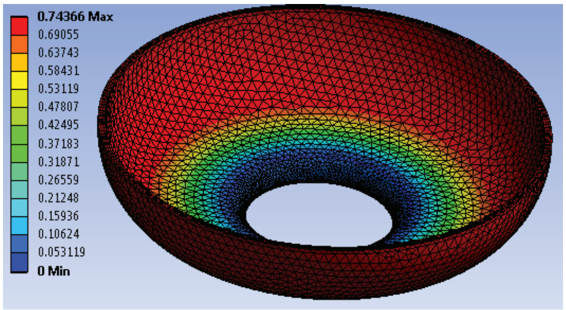

Figure 5: The total deformation (µm) of a half-cell.

The deformed mesh was exported using a Mechanical APDL module and the UPGEOM command. A Finite Element Modeler module was used to create surfaces from the mesh, and a Geometry module to create a solid part from the surfaces. The solid was used in HFSS to run an Eigenmode simulation. The electric field in the cavity can be seen in Figure 6 and the simulated frequencies can be seen in Table 1. One deformed geometry was also exported to CST Microwave Studio [7] and an Eigenmode solution confirmed the HFSS frequency result.

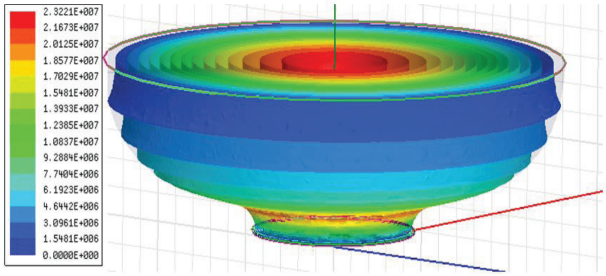

Figure 6: The fields inside a half cell (V/m).

Table 1: Measured and Simulated Half-cell Frequencies

| Cell Type | Measured frequency range (GHz) | Non-deformed simulation (GHz) | Deformed simulation (GHz) |
|---|---|---|---|
| **Male End Cell** | 1.2830-1.2835 | 1.27503 | 1.27500 |
| **Female End Cell** | 1.2874-1.2882 | 1.27499 | 1.27497 |
| **Female Centre cell** | 1.2739-1.2814 | 1.26850 | 1.26847 |
| **Male Centre Cell** | 1.2750-1.2845 | 1.26853 | 1.26848 |

It can be seen from Table 1 that the deformation has a small effect, lowering the frequency on the order of tens of kHz.

### *Coordinate Machine Measurement*

One cell was sent for measurement on a Coordinate Measurement Machine (CMM). This was CM3. Four inside profiles at right angles were measured. The results show the cavity shape is mostly within the 100 µm tolerance, with the main deviation occurring at the iris. The results can be seen in Figure 7.

Figure 7: Representation of the measured cavity profiles. The red lines show the tolerance.

The maximum deviation inwards is 193 µm and outwards is 109 µm. These deviations could be responsible for the deviation from the expected frequency, as simulations reveal ±100 µm change in the radius results in approximately ∓6 MHz error as shown in Figure 8. The frequency errors will be corrected for in the dumbbell trimming stage.

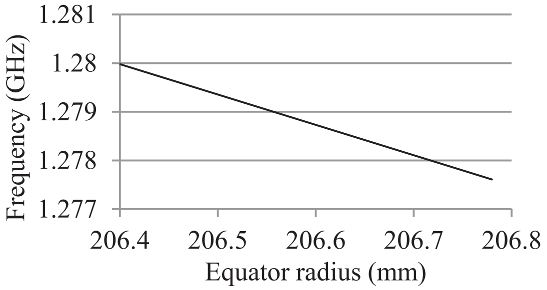

Figure 8: Simulated frequency change with equator radius.

## DUMBELL TRIMMING

### *Frequency Measurement*

When the half-cells have been electron beam welded into dumbbells, the same apparatus will be used to measure the frequency of each half-cell. The method from An et al. [8], using Slater's perturbation theorem will be used.

Each half-cell, once clamped in the measurement apparatus, will be detuned by a small perturbing pin positioned off-centre of the cavity. Six measurements are needed: the frequencies of the π and π/2 modes with no perturbation, $f_\pi$ and $f_{\pi/2}$; the frequencies of the π and π/2 modes perturbing the left half-cell, $f_{p,L,\pi}$, and $f_{p,L,\pi/2}$ and the frequencies of the π and π/2 modes perturbing the right half-cell, $f_{p,R,\pi}$, and $f_{p,R,\pi/2}$. Once these are known the following equations can be used to calculate the frequency of the left and right half-cell respectively.

$$f_{L,\pi} = \sqrt{\frac{f_\pi^2 + f_{\pi/2}^2}{2} + \frac{(f_\pi^2 - f_{\pi/2}^2)(2-R)}{2\sqrt{R+4}}}$$

$$f_{R,\pi} = \sqrt{\frac{f_\pi^2 + f_{\pi/2}^2}{2} + \frac{(f_\pi^2 - f_{\pi/2}^2)(2+R)}{2\sqrt{R+4}}}$$

where

$$R = \sqrt{\frac{f_\pi^2 - f_{p,R,\pi}^2}{f_\pi^2 - f_{p,R,\pi}^2}} - \sqrt{\frac{f_{\pi/2}^2 - f_{p,R,\pi/2}^2}{f_{\pi/2}^2 - f_{p,R,\pi/2}^2}}$$

The end half-cells will be measured directly as they do not form a dumbbell.

### *Trimming*

Once the frequencies are known the deformation due the clamping measurement can be compensated for, and then the amount to trim from the equator of each cell can be calculated. Simulation data was used to find the half-cell sensitivity to trimming. This is shown in Table 2.

Table 2: Half-cell Sensitivity to Trimming at the Equator

| Half-Cell | Sensitivity (GHz/mm) |
|---|---|
| **Male end cell** | 0.0054 |
| **Female end cell** | 0.0056 |
| **Male mid cell** | 0.0051 |
| **Female mid cell** | 0.0053 |

The extra length on each cell is 2.175 mm giving a minimum of 11 MHz trimming range for each half-cell.

## 9-CELL TUNING

### *Measurement*

The dumbbells and end half-cells will be electron beam welded to form the full 9-cell cavity. This will be measured on a bead-pull apparatus. A perturbing bead will be pulled through the cavity and the change in the cavity frequency measured as the bead passes through each cell.

This data can then be interpreted using an equivalent circuit model as seen in Padamsee [9]. Figure 9 shows the equivalent circuit model.

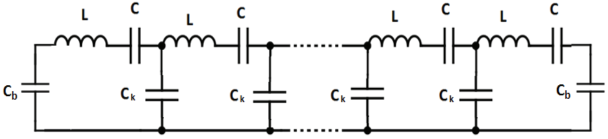

Figure 9: The equivalent circuit model. C is the cell capacitance, L is the cell inductance, $C_b$ and $C_k$ are the beam pipe and cell coupling capacitances respectively.

The model yields an eigenvalue equation representing the cavity. Perturbation theory can be used on a model of an out-of-tune cavity to yield the frequency errors in each cell based on the change in the overall cavity frequency caused by the perturbing bead.

### *Tuning*

Corrections to any cell frequency errors will be performed by pulling or pressing the cell using the bespoke apparatus shown in Figure 10. ANSYS/HFSS simulations will be performed to calculate the level of deformation required to correct for the error in frequency.

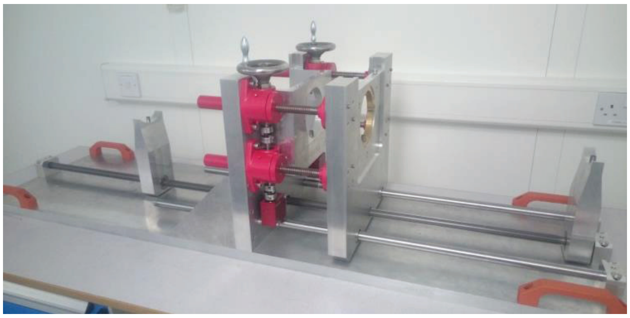

Figure 10: 9-cell tuning apparatus. The cells are clamped at the iris and pulled or pressed to tune.

## SUMMARY

The half-cells that will comprise the 9-cell niobium cavity have been delivered to Daresbury Laboratory. The frequency measurements show the manufacturing process is repeatable, however all half-cell frequencies are higher in frequency than expected from deformed geometry simulations by on the order of 10 MHz. CMM results show the measured cell to be mostly within the 100 μm tolerance, but this tolerance equates to a 12 MHz range of possible frequencies.

The half-cells will be electron beam welded to form dumbbells, and these dumbbells will be tuned to frequency by trimming the length as needed. The trimming will be based on half-cell frequency measurements. Once trimmed the dumbbells will be electron beam welded to form a 9-cell cavity. This cavity will be measured on a bead-pull perturbation apparatus. The results of the bead-pull will inform the tuning process, which will be performed by pressing or pulling each cell.

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