CORNELL'S ERL CAVITY PRODUCTION

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Abstract

The phase 1 R&D program launched in preparation to building a 5 GeV Energy Recovery Linac (ERL) at Cornell, a full main linac cryomodule is currently built, housing six 7-cell cavities. In order to control the beam break-up limit, the shape of the cavity was highly optimized and stringent tolerances on the cavity production were targeted. We will report on the details of the cavity production, the accuracy of the cups forming the individual cells, the trimming procedure for the dumbbells, the cavity tuning and final accuracy of the cavity concerning field flatness, resonant frequency and overall length within this small series production.

INTRODUCTION

The design of superconducting radiofrequency accelerating cavities for the Cornell ERL calls for strict tolerances in the shape of the cavity in order to control the higher order mode spectrum [1].

In preparation for constructing the ERL, a full prototype linac module (MLC) is currently under fabrication [2]. It houses 6 ERL type cavities (7-cells, 1.3 GHz, shown in Fig. 1). This paper will focus on the cavity production, describes the findings and the improvements made to better meet the requirements.

Figure 1: Three ERL cavities built at Cornell to be installed into the prototype Main Linac Cryomodule (MLC).

CAVITY PRODUCTION STEPS

The production process itself has multiple steps where the cavity shape is altered and follows in principle the established pathway of other labs. The process begins with half cells formed by a deep drawing process in which sheet metal of 3 mm RRR niobium is radially drawn into a forming die by a first press at 3 tons, then a second forming press (100 tons). The dies for the centre cells were carefully designed to deal with the spring back effect.

The equators of each cup have an additional straight length on them (approx. 1.5 mm). The purpose of this extra length is to allow for trimming later on to meet the target frequency and length. We will focus on that below when we discuss the dumbbell trimming. Those dumbbells are built in an intermediate step by welding two cups together on their irises.

Ultimately six dumbbells will be welded together by electron beam welding to form the centre-cells of the seven cell cavity and end-cells with end-groups are added. After welding, the assemblies are cleaned by both chemical etching and a high purity water rinse to rid them of any surface impurities that may have accumulated during the production process.

ACCURACY CONTROL

Half Cells

As described earlier the shape (shown in Fig. 2) of the Cornell ERL cavities has been optimized to raise the beam break-up limit above 400 mA. After defining the shape, Monte Carlo simulations have been performed to investigate the tolerances and their impact. It has been found that the shape has to be met within 0.5 mm [3].

In order to guarantee the shape accuracy, all half cells are measured with a coordinate measurement machine (CMM). A rather untypical finding is show in Fig. 3, indicating a maximum deviation of 0.25 mm which is still within the margin. More typically, the achieved accuracy for the shape is better than 25 µm.

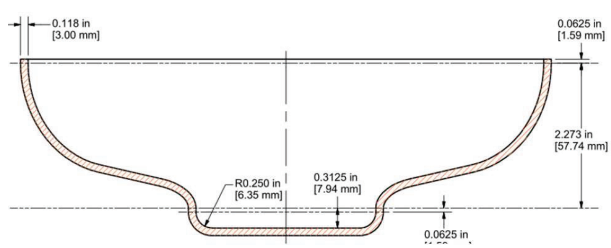

Figure 2: Shape of a centre half-cell for the Cornell ERL cavity giving dimensions.

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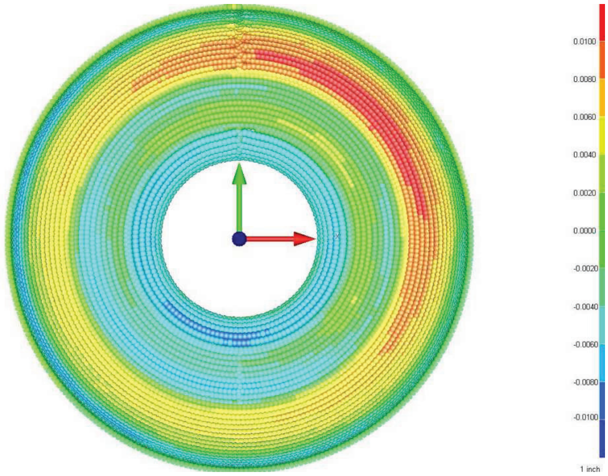

Figure 3: CMM data taken for an untypical "bad" half - cell indicating a maximum deviation from the ideal shape of 0.25 mm (0.01 inch as shown).

Dumbbells

Once two half cells are iris-welded together, dumbbells are formed. Usually, frequency measurements and precise machining were implemented after this second stage. Figure 4 shows the dumbbell frequency measurement set-up that has been redesigned in order to minimize measurement errors- as we found that the old set-up was deforming the dumbbells while applying the necessary pressure on the RF contacts (see below for details).

The principle of the measurement and the data extraction has been reported before [4]. Based on the measured frequencies of the dumbbells the excessive length of the equator region is trimmed. It is important to understand how the frequency of the dumbbell changes as they are trimmed so that the target frequency is met and accurate predictions for the cavity length can be made. In the past, we focussed only on getting the frequency right.

The results of the production can be seen in Tab. 2. Each cavity was long, as well as low in frequency. Adjusting the frequency through the use of tuning served only to lengthen the cavities even further. This does not necessarily have an impact on the higher order mode

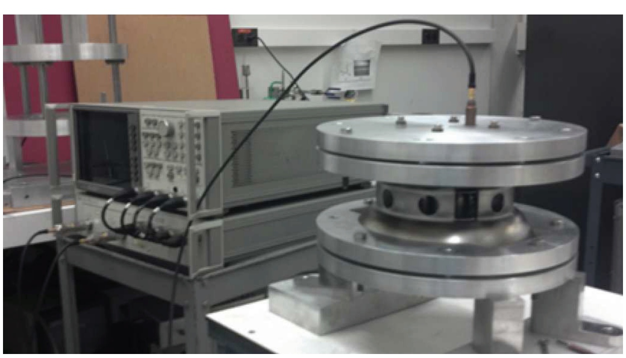

Figure 4: Improved dumbbell apparatus. This set-up allows measuring the frequencies of the dumbbell with deforming the cells meanwhile ensuring a good RF contact.

Table 1: Length and Frequency of the First 3 ERL Cavities

Pre-Tuning

	Length (mm)	Frequency (MHz)
ERL7-002	1161	1298.46
ERL7-003	1161.5	1298.459
ERL7-004	1160.7	1298.498

Post-Tuning

	Length (mm)	Frequency (MHz)
ERL7-002	1165.9	1297.462
ERL7-003	1163.9	1297.504
ERL7-004	1162.1	1297.541

properties and the BBU limit. However, the finished cavity must fit inside the cryomodule which adds another specification to the cavity production: the seven cell cavity has to be within ±1 mm of its nominal length (1160.0 mm) after final field flatness tuning (better than 95% with the pi-mode frequency of 1298.985 kHz).

In an effort to avoid a situation such as this in the second production series of the three stiffened cavities, the previous production steps were analysed and a new strategy was formed.

Root Cause of Frequency and Length Discrepancy

Before attempting to develop a protocol for frequency and length control during production, an effort to find the root cause of the discrepancy between the target cavity frequency and the manufactured cavity frequency was made. After many tests, it was determined that the fixture used to measure the resonant frequency of dumbbells reported an incorrect result. The original fixture, based on the JLab design [5], ensures adequate RF contact by pressing the dumbbell between two copper plates using a power screw. The middle of the dumbbell is unsupported. This can lead to a deformation of the dumbbell and subsequent shift in resonant frequency. To combat this problem, a new fixture was designed and constructed.

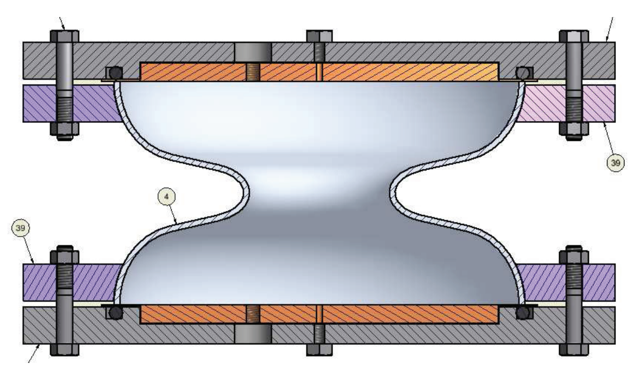

Figure 5: Cross-section of new dumbbell apparatus.

The revamped RF measurement fixture design was based on the DESY design used for tesla cavities [6]. Figure 5 shows the concept of the new apparatus as built. Two aluminium plates are placed on the ends of the dumbbell. Inside these plates are copper RF contact plates. Aluminium plates are placed on the outer contour of the half-cells of each dumbbell. These plates are bolted to the equator plates for a good RF contact.

The middle plates in this fixture serve to brace the half-cells of the dumbbell so that adequate force may be applied to obtain a sufficient quality factor for measurement, while avoiding deformation of the half-cells.

Frequency Changes During Production

The half-cell contour was designed using FEM to calculate the correct resonant frequency at 1.8 K under vacuum. The room temperature frequency at STP is then extrapolated from this calculation.

The half-cell contour, when combined with the end-groups, drives the overall cavity length. However, several manufacturing and processing steps can have an effect on either length, frequency, or both. For example, etching the cavity will drive the frequency of the cavity down, but has no consequence on the overall length. However, field flatness tuning can be used to adjust the frequency of the cavity while simultaneously changing the overall length of the cavity.

Table 2: Various Manufacturing Gradients

Dumbbell Trimming	5	kHz/µm
Etching	10	kHz/µm
Tuning	430	kHz/mm

It is important to know how each process will affect both the frequency and length of a cavity. To do so, each process' "gradient" must be known. For example, the tuning gradient is 430 kHz/mm. This means tuning the cavity will change its frequency by 430 kHz for every on millimetre. Other gradients are shown in Tab. 2.The dumbbell trimming gradient is, perhaps, the most salient variable during production. This gradient was calculated

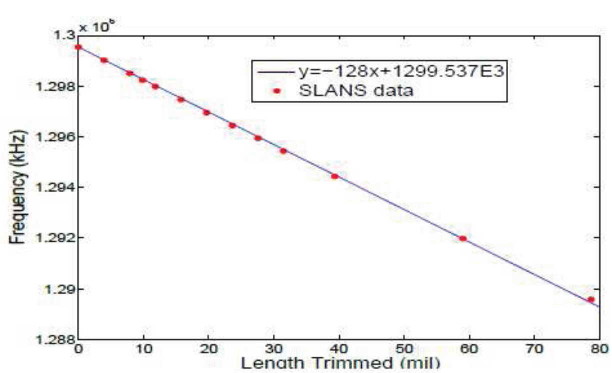

Figure 6: Calculated trimming gradient using the SLANS Code.

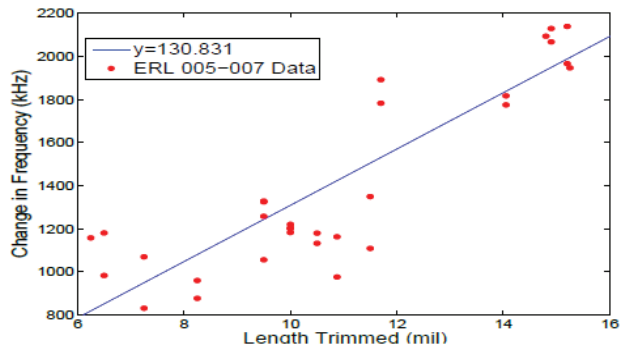

Figure 7: Measured trimming gradient using the newly designed dumbbell apparatus.

using SLANS and was found to be very linear (Fig. 6).

Experimental trims of various dumbbells at various lengths confirmed this value (fig. 7). The experimental trimming gradient is approximately 5.2 kHz/µm. This is within 1.5% of the theoretical value, giving good agreement between theory and experiment. The good agreement is partially due to the improved design for the RF measurement of the dumbbells which now ensures

Frequency and Length Control for the 2nd Batch of 3 Cavities

During the second series of stiffened cavity production, the following quality control steps were applied:

- Coordinate measurement (CMM) of all half-cells in both untrimmed and trimmed states.
- CMM of untrimmed welded dumbbells.
- Frequency measurement of all dumbbells in the untrimmed state.
- CMM and RF measurement of all dumbbells after trimming.

Steps 1 & 2 were performed to verify all half-cell contours were within acceptable limits. Steps 3 & 4 were used to derive the cavities length and frequency.

To insure the cavity being produced would fall within both the frequency and length tolerances, the following algorithm was used (which represents the change in strategy since the first batch):

$$\Delta L = d_{Trim} + d_{Tune}$$

$$\Delta F = d_{Trim} \times \Delta_{Trim} + d_{Tune} \times \Delta_{Tune}$$

Where, d_{Trim} and d_{Tune} are the change in length due to trimming the dumbbells and tune the cavity, respectively. Δ_{Trim} and Δ_{Tune} are the trimming gradient and tuning gradient, respectively. Using these two equations, it is possible to find a solution that will yield the correct cavity length after frequency and length after trimming and tuning.

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Table 3: Dumbbell Length and Frequency (untrimmed, upper table and trimmed, lower table)

Dumbbell	A	B	Frequency (MHz) A	Frequency (MHz) B	fpi (mean) (MHz)	Length (mm)
CC	79	83	1296.815	1296.782	1296.800	115.443
CC	86	98	1296.686	1296.864	1296.777	115.900
CC	78	81	1296.661	1296.706	1296.685	115.938
CC	97	101	1296.763	1296.852	1296.809	115.900
CC	104	108	1296.647	1296.924	1296.788	115.653
CC	111	113	1296.818	1296.738	1296.780	115.741

Dumbbell	A	B	Frequency (MHz) A	Frequency (MHz) B	fpi (mean) (MHz)	Length (mm)
CC	79	83	1298.635	1298.635	1298.635	115.443
CC	86	98	1298.635	1298.635	1298.635	115.900
CC	78	81	1298.635	1298.635	1298.635	115.938
CC	97	101	1298.635	1298.635	1298.635	115.900
CC	104	108	1298.635	1298.635	1298.635	115.653
CC	111	113	1298.635	1298.635	1298.635	115.741

SECOND SERIES PRODUCTION OF STIFFENED CAVITIES

Six dumbbells were selected for a prototype fabrication in the second series of cavity production (ERL7-005). These dumbbells are listed, along with their pre- and post-trimmed lengths in Tab. 3. (Note that the weld shrinkage has been accounted for in the overall length calculation.) At the target frequency of 1298.985 MHz, each these dumbbells would be shorter than the target dumbbells length, adding up to a cavity that was too short, but at the right frequency. Figure 8 shows the variance in both frequency and length of the six selected dumbbells before and after trimming. The pre-trim dumbbells have some variance in both length and frequency, but this is to be expected, as no frequency control protocols have been applied yet. The post-trim dumbbells, however, are very close in frequency relative to one another, while varying in length by approximately 0.5 mm. The dumbbells' target frequency was changed to 1298.635 MHz in an effort to correct the lack of length at the correct frequency. By leaving an extra 0.7 mm per half-cell on each dumbbell after trimming, the resonant frequency of the cavity would be too low by 350 kHz, but the length would only be +1.1 mm. It is assumed that, tuning the cavity by 350 kHz to the correct pi-mode frequency would lengthen the cavity by approximately 0.8mm, bring the finished cavity to the tolerable length, and correct frequency. (Note: The target length has been changed from 1160 mm to 1159 mm for this production series)

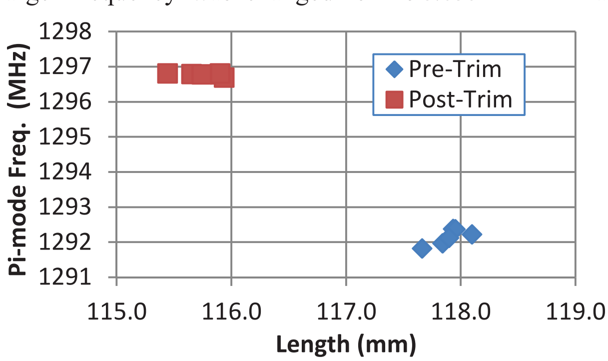

Figure 8: Variance of dumbbell frequency before and after trimming.

The dumbbells also have a pre-determined extra length left on them prior to welding to account for weld shrinkage. Each equator is grooved as a preparation for the weld to allow material to fill the groove and leave a relatively smooth surface.

After the final welding and the bulk BCP, where 140 µm of inner surface is removed, every cavity is tuned for field flatness. By means of a bead-pull, the field distribution is measured. The profile can be adjusted by stretching or compressing individual cells. Figure 9 shows

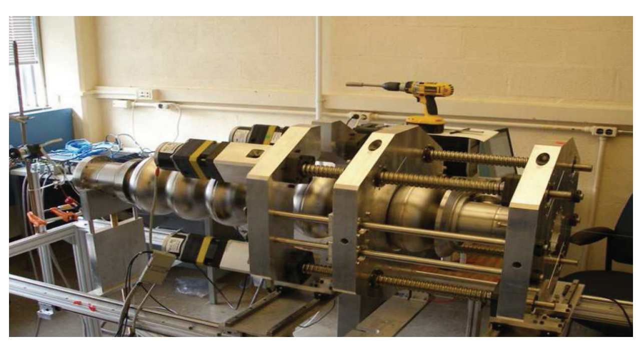

Figure 9: Bead-pull measurement and field flatness tuning set-up.

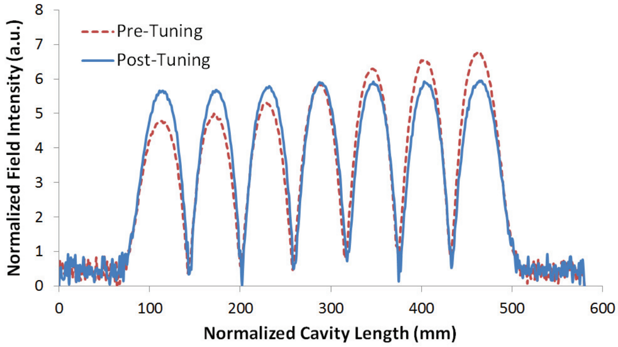

Figure 10: Bead-pull measurement of the cavity field distribution as fabricated and after final tuning.

the set-up, in Fig. 10 we plot the measured field flatness directly after fabrication and the final profile after the field tuning. During this tuning, the pi-mode frequency will be adjusted as well to match the target frequency.

CONCLUSION

Cavity ERL7-005 has just recently come off of the production line. ERL7-005's length is 1157.1mm and its' pi-mode frequency is 1298.259 MHz with 79% field flatness. This results differs from the predicted above. ERL7-005 is approximately 1.1mm too short in length (1157.1 mm overall) and 400 kHz (1298.259 MHz) too low in frequency. The cause of this is still under investigation.

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