JLAB SRF CAVITY FABRICATION ERRORS, CONSEQUENCES AND LESSONS LEARNED*

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Abstract

Today, elliptical superconducting RF (SRF) cavities are preferably made from deep-drawn niobium sheets as pursued at Jefferson Laboratory (JLab). The fabrication of a cavity incorporates various cavity cell machining, trimming and electron beam welding (EBW) steps as well as surface chemistry that add to forming errors creating geometrical deviations of the cavity shape from its design. An analysis of in-house built cavities over the last years revealed significant errors in cavity production. Past fabrication flaws are described and lessons learned applied successfully to the most recent in-house series production of multi-cell cavities.

INTRODUCTION

The ensemble of cavities reviewed comprise 1.5 GHz High Current (HC), High Gradient (HG) and Low Loss (LL) type SRF multi-cell cavities, the latter designed for the 12 GeV upgrade program of the multipass recirculator CEBAF at JLab. Five-cell HC cavities have been designed for high average current applications in excess of 10mA [1]. Seven-cell HG and LL prototypes have been scrutinized to demonstrate their suitability for CEBAF assembled in the cryomodule *Renascence* [2] operating from 2007-2009. While both have shown similar operational achievements, the LL cavities have been eventually favored due to the superior cryogenic efficiency. Due to thermal issues during the initial testing stage of *Renascence* in 2005 [3], alterations towards a final cavity design ("*C100*" for CEBAF 100 MeV cryomodule) were made focusing on improving the cooling concept that has led to early quenches [4]. Noticeable are the decision to sacrifice HOM damping performance and mechanical integrity at the same time by omitting a) the Higher Order Mode (HOM) end group on one side of the cavity and b) the cell stiffening rings. Two such cavities (C100-1 and C100-2) were built rapidly in 2006 for demonstration tests in a dedicated quarter cryomodule (2006-2007) with satisfying RF performance. This has given confidence to award the manufacture of 80 *C100* cavities (plus six spares) to industry, namely Research Instruments GmbH, Germany [5], who commenced with fabrication in July 2009 and completed delivery by March 2011 [6]. Note that these pre-tuned cavities are not part of the review. In parallel, JLab has completed the in-house fabrication, chemical post-processing and vertical high power testing of eight *C100* type cavities in 2010 dubbed *R100*. Cryomodule assembly was completed in April 2011 and horizontal tests were conducted in April-May 2011 with results presented in [7]. The cryomodule has since been installed in CEBAF awaiting beam operation.

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While all above mentioned cavities were made from fine grain (RRR > 250) niobium, two additional C100 cavities were built from large grain niobium (J100-1 and J100-2) to study possible advantages concerning post-processing and performance.

FABRICATION ERRORS

Identifying Error Sources

The frequency deviation of the accelerating TM_{010} π-mode to a target frequency and its field flatness along the cells have been consulted as indicators for fabrication errors of "as-built" cavities, i.e. before undergoing routine post-production bench tuning. Table 1 reveals that frequencies were consistently too high, exceeding 4 MHz in some cases. One consequence of such large errors is that the post-production tuning requires "brute force" to deform individual cells to re-tune and re-flatten the TM_{010} π-mode at the same time. E.g. LL *Renascence* cavities were shortened by more than 1 cm (!) after production.

Table 1: Frequency deviation from target and field flatness as measured prior post-production tuning (after bulk BCP and heat treatment), n.m. = not measured

Cavity ID	TM_{010} π-mode off tune MHz	Field flatness in ±% from average
HG001	+1.69	-7 / +5
HG002	+2.06	-38 / +51
HG003	+2.14	-15 / +16
HG004	+1.49	-17 / +35
HG005	+1.77	-17 / +21
HG006	+2.11	-27 / +23
HG007	+1.90	-9 / +16
HG008	+1.59	-9 / +12
LL001	+4.01	-23 / +39
LL002	+3.92	-13 / +12
LL003	+3.60	-21 / +44
LL004	+3.94	-12 / +26
C100-1	+2.70	n.m.
C100-2	+2.46	-21 / +38
HC-1	+3.91	-4 / +5
HC-2	+3.99	-6 / +8
J100-1	+4.18	-33 / +43
J100-2	n.m.	n.m.

Springback after Deep-Drawing

A significant fabrication error arises after forming niobium sheets in half cells by deep-drawing. Springback can cause serious deviations from the ideal shape due to material internal stresses, when the dies are released after the forming process. To quantify prevalent springback-induced errors, two nominal LL mid cells (CC01, CC02) made from fine grain niobium sheets (1/8" thickness) have been deep-drawn, while obeying usual procedures and using existing die sets. Subsequently, inner contours have been measured for each cell with a Coordinate Measuring Machine (CMM) at four different planes, azimuthally spaced by 90 degrees (A, B, C and D). The measured contours have been used as input for the FEA code ANSYS for modal analysis. Fig. 2, plotting the deviation of the TM_{010} π-mode frequency from that of the ideal cell shape for each contour, reveals average errors in the range of +3.2-3.5 MHz (red bars). The CMM revealed that the area close to the cell equator is pushed inwards resulting in the largest errors, while the iris area is comparably less affected. The differing errors (blue bars) for the same cell (± ~1MHz) indicate that cells are not fully circular.

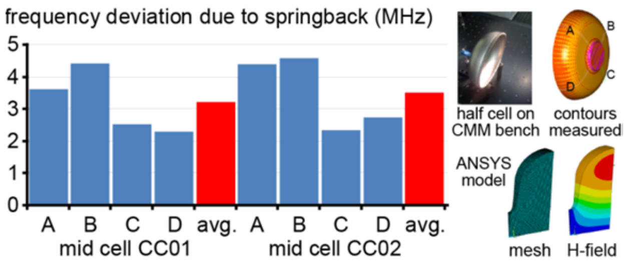

Figure 2: Frequency deviations of two deep-drawn cells from the ideal shape as measured at four different planes.

RF Dumbbell/Half Cell Measurements

Once the half cells are formed, irises are trimmed and two half cells are joined by EBW resulting in “dumbbells”, except for end half cells joined to beam tubes. The weld shrinkage is taking into account by leaving irises oversized accordingly. Equators are left oversized for later tuning/trimming to a (warm) target frequency. At this stage, the frequency error due to springback can be compensated. The prevalent errors in Table 1 however imply additional methodical flaws.

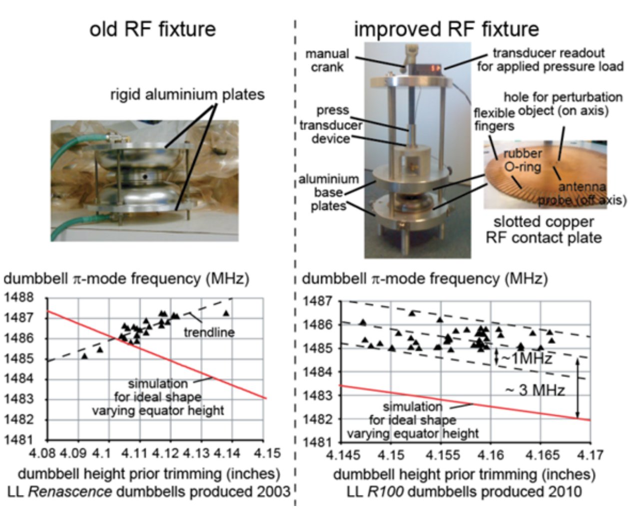

Figure 3: Prevalent frequency errors of past fabrication methods (left) cured by improved tooling (right).

Tuning to a target frequency requires evaluating the trimming amount precisely. For this procedure each dumbbell is sandwiched between two plates to form a closed two-cell oscillator resonating in 0-mode and π-mode, respectively. Established perturbation theories can be used to extract the pure π-mode of each cell. The accuracy depends strongly on how well RF contacts can be made around the equators. This is indicated by the achievable Q-value as a figure of merit. In former attempts, dumbbells have been pressed between two rigid plates in a simple fixture (Fig. 3, top left). Rigid plates however do not guarantee reasonable RF contacts, and large frequency errors were prevalent, even with unphysical trends when compared to simulations (Fig. 3, bottom left). A more appropriate RF fixture has been developed to manufacture *R100* cavities utilizing flexible RF contact plates (Fig.3, top right) as done at DESY resulting in a frequency accuracy < 50 kHz. The deviation of 3MHz ± 1MHz to the nominal shape correlates well with the assessed springback error, as detailed above.

Cell Equator Trimming

With a given target frequency and a trimming amount determined individually for each cell equator, the dumbbells and end cells can be trimmed to final size. The trimming accuracy of the tooling used in the past (Fig. 4, left) has been investigated by means of the discrepancy of requested to actually achieved dumbbell heights after machining. Hereby, a consistent shortage with an error of ~0.01" has been encountered. Based on a linear trimming sensitivity of 130 kHz/0.001", this yields a frequency error as high as +1.3 MHz in average. The large trimming uncertainties were found to correlate with problems in levelling out the machinable equators, when the dumbbells are resting within sleeves on a rather small suspension area. A new trimming fixture has been developed for *R100* cavity production, which provides a better suspension area and accommodates both dumbbells and end cells (Fig 4 middle/right). The fixture has proven to minimize trimming errors within 0.00022"-0.0023", thereby limiting the average frequency error to ~300 kHz.

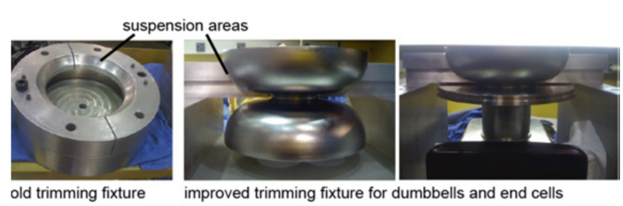

Figure 4: Old (left) and improved fixture (middle, right) for cell equator machining.

Thermal Effects

The weld shrinkage due to EBW can be geometrically assessed precisely. It has been found experimentally, though, that this shrinkage does not account for the overall frequency shift. Instead, an additional increase averaging to about +750 kHz per cavity has been measured. It is believed that this frequency change is related to a stress relief during the EBW process in the heat affected equatorial zone (weld temperatures

~2500°C). Furthermore, a similar effect has been found during the post-processing cycle after BCP, when cavities are routinely baked at 600ºC for 10 hours for hydrogen degassing. Hereby a frequency increase of +270 kHz was encountered in average among eight *R100* cavities. A CMM measurement of the active length change after heat treatment was carried out for cavity *R100-8* showing an increase of 0.53 mm. This geometrical change is in accordance to an increase in frequency by an inward equatorial movement. Field profile measurement before and after the heat treatment verified that the geometrical changes are very consistent along the cells, since the field flatness did not alter significantly.

Chemical Treatments

SRF cavities generally have to bear chemical treatments like buffered chemical polishing (BCP) and Electropolishing (EP). It became apparent that the vertical BCP at JLab is typically very non-uniform since carried out without a diverter system. This has left the surface around equators less etched than around irises by roughly a factor of two. While a uniform (desired) surface removal would reduce the frequency at a rate of ~15 kHz/µm, a factor of four less has been measured. Consequently, with the assumption to remove a uniform damage layer of ~150 µm, the target frequency can err by as much as +1.7 MHz. A very non-uniform removal has been analyzed for the horizontal EP process as well, although the EP targeted a 30 µm surface removal yielding a frequency reduction of merely ~-160 kHz per cavity. Furthermore, chemistry-induced field flatness deteriorations have been studied for the BCP and EP processes by measuring cavity field profiles before and after chemical treatments. In case of EP, the beam tubes were etched preferably and no strong tendency for differential etching along the cells could be witnessed. However, BCP has shown to lower field amplitudes within the end cells by up to 20%.

LESSONS LEARNED

For the production of *R100* cavities, prevalent fabrication flaws and erroneous target frequencies of the past have been eliminated. Table 2 summarizes the frequency and field flatness of "as-built" cavities with partly one order of magnitude improvement, when compared to previous data comprised in Table 1. Therefore, "brute force" post-production bench tuning could be avoided. The first cavity in series, *R100-1*, has been utilized as a "calibration" cavity in order to scrutinize all major systematic errors, which resulted in the largest frequency error. The findings were fed back for subsequent cavities "on-the-fly" for major improvements. The *R100* dumbbells have been thoroughly sorted to equalize cell lengths. This not only produced rather flat fundamental field profiles throughout, but also symmetrized the field distribution of HOM fields to yield a consistent broadband HOM damping performance among all cavities in the cryomodule string [8].

Table 2: Frequency deviation from target and field flatness for *R100* cavities as measured prior post-production tuning (after bulk BCP and heat treatment)

Cavity ID	TM_{010} π-mode off tune MHz	Field flatness in ±% from average
R100-1	1.66	-10.3/+6.9
R100-2	0.07	-7.9/+7.6
R100-3	0.31	-13.4/+7.7
R100-4	0.41	-5.4/+3.1
R100-5	0.17	-13.6/+6.5
R100-6	0.37	-5.5/+4.2
R100-7	0.18	-7.5/+5.1
R100-8	0.26	-3.4/+2.7

CONCLUSION

Standard SRF cavity fabrication procedures as routinely applied at JLab have been critically reviewed by means of 1.5 GHz cavities built over recent years. It has been revealed that cavities cannot be built closely to a reference design without compensating springback effects responsible for MHz errors. Systematic errors in RF measurement and dumbbell machining together with a negligence of the real effects of chemical treatments can explain past prevalent fabrication flaws.

Methods and goals have been significantly improved for the most recent *R100* cavity cryomodule string fabrication. Several new important phenomena have been identified such as frequency shifts encountered after heat treatment and after electron beam welding related to thermal effects changing cell geometries. All cavities could be built with significant improvements in frequency and fundamental field flatness, hence requiring only minor post-production tuning interventions. Minor bench tuning together with consistent fabrication and post-processing methods in turn allow building cavities with tolerable assembly lengths. This is of importance ever since accelerator cryomodules aim to maximize the real-estate gradient relocating beam line components and bellows to the end of the cryomodule thereby demanding for improved cavity length accuracy and alignment procedures.

More comprehensive details on fabrication errors and relevant concerns are summarized in ref. [9].

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