RESULTS OF CAVITY SERIES FABRICATION AT JEFFERSON LABORATORY FOR THE CRYOMODULE *R100**

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Abstract

A series production of eight superconducting RF cavities for the cryomodule *R100* was conducted at JLab in 2010. The cavities underwent chemical post-processing prior to vertical high power testing and routinely exceeded the envisaged performance specifications [1]. After cryomodule assembly, cavities were successfully high power acceptance tested. In this paper, we present the achievements paving the way for the first demonstration of 100 MV (and beyond) in a single cryomodule to be operated at CEBAF.

INTRODUCTION

The cryomodule (CM) *R100* is identical in design to each of the ten 12 GeV CEBAF upgrade CMs (*C100*) currently under construction at JLab. *R100* is intended for CEBAF's injector to boost the extraction energy to the demands in the once upgraded recirculator. Eight *R100* cavities were built at JLab from early to mid-2010. At the same time, the industrial fabrication of 86 *C100* cavities was still ongoing [2]. The *C100/R100* CMs make use of eight seven-cell "Low Loss" type niobium cavities for CW operation at 1497 MHz bathed in 2.07 K superfluid Helium. The cavity RF specification calls for an accelerating field of $E_{acc} = 19.2$ MV/m at an unloaded quality factor of $Q_0 = 7.2e9$. This could be exceeded routinely in vertical tests for all *R100* cavities. The CM was then completed by April 2011 and successfully qualified in JLab's Cryomodule Test Facility (CMTF). *R100* is currently installed in CEBAF's south linac awaiting first beam tests. In the following, the methods and tools for the precise cavity fabrication are described, presenting RF performance results thereafter.

R100 CAVITY FABRICATION

Cavity production was done by standard techniques utilizing deep-drawing of (3 mm) niobium sheets and electron beam welding (EBW) of cavity cells. Beam tubes are rolled and welded along longitudinal seams. The most complex part is the HOM damping end group including the DESY-type coaxial couplers that requires various machining, rolling and welding steps. Fig. 1 reflects the principal fabrication sequence. To avoid large fabrication errors, prevalent in recent years, several alterations were put into effect by scrutinizing and improving methods and tooling "on-the-fly" ([3], [4]). The sequence starts with an already deep-drawn half cell (a). Half cells are oversized initially on each side after forming. The irises are then trimmed directly to the reference design. The equators at this stage are machined flat and left intentionally longer (~0.1") to allow frequency tuning by custom trimming. The half cells are inspected for any damage or irregularities and cleaned by degreasing in a solution of ultrapure water (UPW) and detergent (> 20 min) under ultrasonic agitation, rinsing off the detergent with UPW and immersing the half cells (1.5-2 min) in a container with a Buffered Chemical Polishing solution (BCP). Afterwards half cells are rinsed properly again with UPW and blown dry with filtered Nitrogen before sealed in a nylon bag. Chemical cleaning is particularly crucial to prepare weld surfaces prior to EBW by removing all damaged and oxide layers as well as foreign material inclusions. Two mating sets of half cells are then joined by EBW to a so-called "dumbbell" (b). The end groups containing either the Higher Order Mode (HOM) (c) or input power coupler (d) are manufactured in parallel.

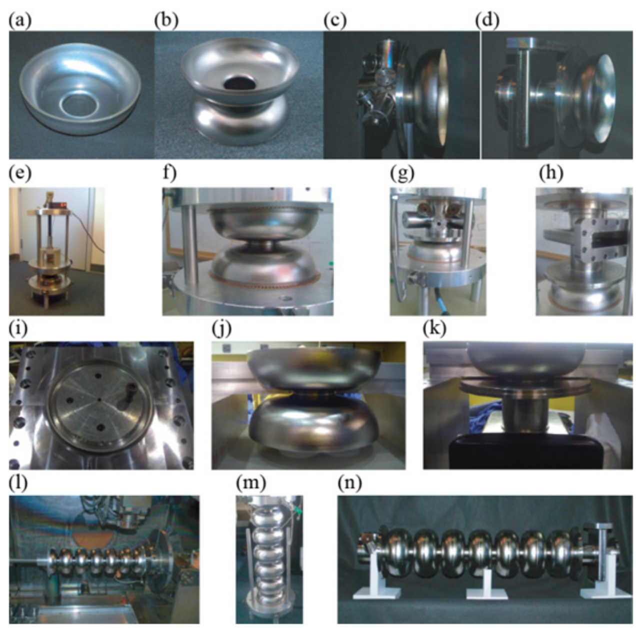

Figure 1: *R100* cavity fabrication sequence (cf. text).

A new RF measurement fixture (e) was designed that can accommodate both dumbbells (f) and the endgroups (g, h), respectively. It is used to determine the exact trimming amount of cell equators by measuring the TM_{010} π-mode frequency with knowledge of a previously assessed trimming sensitivity. Whereas the π-mode can be measured directly for the end groups, the dumbbells form a two-cell oscillator resonating in a 0-mode and π-mode, respectively. One requires the π-modes of the individual half cells, which are determined by perturbation techniques in this case. For trimming itself, a new fixture (i) was constructed to properly sustain dumbbells (j) and

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end groups (k) providing good machining precision. After final trimming, equators are prepared with the weld steps. Any obvious blemishes in the interior (e.g. pits, or scratches) are mechanically polished and each cell is chemically cleaned again.

In the next step, all six dumbbells per cavity are stacked carefully together in a mandrel for use in the EBW furnace and welded successively (l). The π-mode frequency of this "inner" cavity is measured afterwards (m). Each end group can then be tailored to the same frequency by properly trimming end half cells as described above. After obligatory chemistry for weld joints, the "inner" cavity is welded to both end groups to produce a cavity as shown at stage (n). This procedure, together with proper dumbbell sorting, proved well to produce flat TM_{010} π-mode field profiles among all cavities. A typical result is shown in Fig. 2 left plotting the "as-built" field profile measured before post-production tuning (here for *R100-1*).

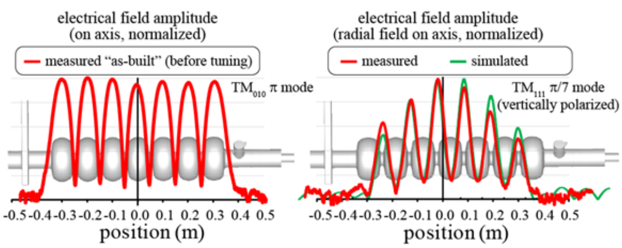

Figure 2: Typical result of an "as-built" flat fundamental mode and symmetric TM_{111}-like $\pi/7$ HOM field profile.

R100 cavities have been built also with focus on symmetrizing HOM fields, i.e. to avoid tilting effects. Since cavities employ only one HOM end group by design, such tilted modes can strongly elevate the loaded Q. E.g. the TM_{111}-like propagating HOM pair resonating around 2.9 GHz - with the highest shunt impedances among all dipole modes - is prone to tilt as evidenced in many *C100* cavities delivered by industry. The typical field profile in *R100* cavities however are comparably well symmetrized as shown in Fig. 2 right (for *R100-1*) to provide consistent damping efficiency. This has been analyzed for the complete cavity string in the CMTF [5]. It should be mentioned that a new automatic pole fitting routine has been developed especially for the cryomodule string measurements. It allows accomplishing an otherwise enormous experimental effort in unprecedented short time [6], yet is applicable to any RF resonant structure.

Table 1 eventually lists the frequency deviation from the desired target as well as the field flatness of "as-built" cavities. These achievements represent partly an one order of magnitude improvement when compared to similar data of previous production years at JLab (further details in [3], [4]). Note that the first cavity in series, *R100-1*, has been used as a "calibration" cavity to scrutinize all major systematic errors, i.e. resulting yet in a larger frequency deviation from the target frequency. The findings for *R100-1* were fed back for subsequent cavities for improvements "on-the-fly".

Table 1: Frequency deviation from the target frequency and field flatness of "as-built" *R100* cavities*

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

* as measured before post-production bench tuning, i.e. after bulk BCP and heat treatment.

POSTPROCESSING

Cavities underwent an established post-processing procedure, an excerpt of which is illustrated in Fig. 3. It comprises ultrasonic degreasing in water-soap detergent (micro-90). Then a bulk BCP is carried out (~150 µm) with ultrapure water rinsing and the cavity is dried overnight. This is followed by a vacuum furnace heat treatment (a) at 600ºC for 10 hours for hydrogen degassing. Interestingly, a consistent frequency shift among cavities after this treatment - as in case of EBW - amounting to 270 kHz in average was evidenced. The field flatness of cavities did not deteriorate, which indicates thermal deformations of uniform nature.

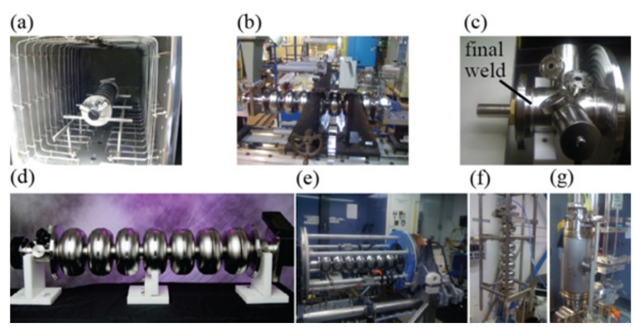

Figure 3: Various post-production and -processing steps.

A post-production bench-tuning (b) is a routine measure after bulk BCP and heat treatment. This leads to a length change of the cells to an amount depending on the initial frequency error. The original fabrication procedure mandates to carry out a tailored weld of a beam tube extension (with flange) at the HOM end group side (c) to achieve the required assembly length of 1 m within ± 1mm. This final weld completes the cavity (d), which then is ready for the remaining post-processing steps. These include ultrasonic degrease and a final light EP (e) (~30 µm). Another ultrasonic degrease is done to remove sulfur residues after EP followed by a vertical ultrapure high pressure water rinse (HPR) (1250-1300 psig) aimed to flush out any remaining particulates. Cavity flange components are then assembled in a class 10 clean room. A HPR is performed afterwards and the input probes and pump out flange assembled at beam tubes. The cavity equipped in its vertical cage (f) is leak checked and receives a vertical in-situ bake-out (120ºC for 24 hrs.).

Eventually it is moved in JLab's Vertical Test Area (VTA) for high power qualification. *R100* cavities have been tested first without the stainless steel helium vessel (HV) to gain confidence with several post-processing handling issues encountered. This is a consequence of the mechanical weakness of the *C100/R100* cavities since cell stiffening rings are omitted per design. The cavities are therefore prone to distort rather easily. This in turn impairs the frequency and field flatness. It was tried to limit such effects by improved quality assurance, particularly during the HV welding process, after which a re-flattening of the fundamental mode is not possible anymore. A dedicated vertical alignment fixture was employed for vertical HV tack welding (g), while final TIC-welding was performed on a horizontal bench to result in the cavities ready for CM assembly, after a final HPR.

RF PERFORMANCES

Fig. 4 shows the achieved RF performance results of all cavities plotting Q_0 versus E_{acc} for cavities without HV (top), after HV welding (mid) and after cryomodule installation in the CMTF (bottom), respectively.

Without HV, it was tried to elaborate performance limits, though only *R100-4* was tested to its quench limit at 37.4 MV/m. In fact, tests for *R100-7* were prematurely aborted due to a facility shutdown at the time, whereas *R100-2*, *R100-4* and *R100-8* were limited by the available RF power. VTA hardware improvements have been made throughout the course of cavity qualification including an upgrade of the RF amplifier. Stricter administration limits were enforced successively to mitigate risks. E.g., the maximum allowable field emission (FE) measured at Dewars was set to 1 mSv/hr. This aims to prevent from potential field emitter explosions. In this sense, *R100-3*, *R100-5* and *R100-6* were field FE limited. Nevertheless, all cavities showed exceptional results exceeding the CEBAF specification, which is indicated by the red star in Fig.4 lying on the 29 W dynamic loss allowance curve.

When testing cavities after HV welding, *R100-4* and *R100-5* were found to quench at ~23MV/m and ~33.5 MV/m, respectively. Typically though, the previous excellent results could be retrieved. The final HPR after HV welding helped to reduce FE levels in some cases. To accelerate qualification throughput, a further limit was obeyed more strictly, i.e. to cease testing when fields reach E_{acc} = 27 MV/m, which is still far beyond specification. This is reflected in Fig. 4 (mid).

Acceptance testing in the CMTF was carried out from April-May 2011. Except *R100-3* and *R100-6,* which were constraint by FE, cavities were quench-limited. The cryomodule achieved ~130 MV at safe operating fields, i.e. 0.5-3 MV/m below quench limits among cavities. A Q_0-degradation in the CM is typical, when compared to the vertical performance. The cause is still a matter of investigation. To some extent it may relate to elevated static magnetic fields originating from various CM components less efficiently shielded.

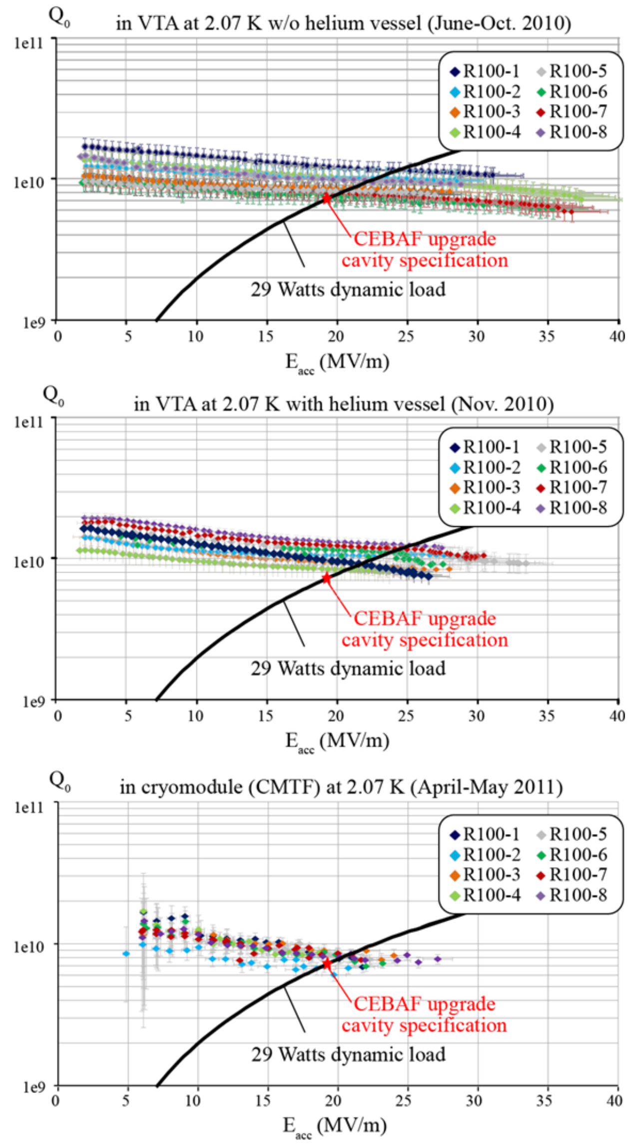

Figure 4: *R100* cavity RF performances in the VTA w/o HV (top), with HV (mid) and in the cryomodule (bottom).

CONCLUSION

The *R100* cryomodule cavities have been built with comparably high precision achieving new standards at JLab. The cavities routinely exceeded CEBAF's operational specification in the VTA. The successful cryomodule acceptance paves the way for the first demonstration of 100 MV in a single cryomodule at CEBAF, i.e. four times higher than in original cryomodules built about two decades ago.

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