PRODUCTION AND TESTING EXPERIENCE WITH THE SRF CAVITIES FOR THE CEBAF 12 GeV UPGRADE*

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Abstract

The CEBAF recirculating CW electron linear accelerator at Jefferson Lab is presently undergoing a major upgrade to 12 GeV. This project includes the fabrication, preparation, and testing of 80 new 7-cell SRF cavities, followed by their incorporation into ten new cryomodules for subsequent testing and installation. In order to maximize the cavity Q over the full operable dynamic range in CEBAF (as high as 25 MV/m), the decision was taken to apply a streamlined preparation process that includes a final light temperature-controlled electropolish of the rf surface over the vendor-provided bulk BCP etch. Cavity processing work began at JLab in September 2010 and will continue through December 2011. The excellent performance results are exceeding project requirements and indicate a fabrication and preparation process that is stable and well controlled. The cavity production and performance experience to date will be summarized and lessons learned reported to the community.

INTRODUCTION

The 12 GeV upgrade program at Jefferson Lab aims to increase the overall energy of the CEBAF accelerator from 6 GeV to 12 GeV through the installation of an additional 80 SRF cavities in ten - C100 cryomodules. (The term C100 refers to the ~100 MV acceleration gain in each cryomodule in comparison to the original C25 cryomodules installed in CEBAF in the early 1990s)[1] In addition to the cavity work that will be covered in this paper, there is significant work on modifying the bending magnets for the arcs to account for the higher energy electron beam, as well as numerous refurbishment efforts of the existing three experimental halls. In addition a fourth experimental hall is being built to take advantage of the full 12 GeV electron beam energy.[2] This paper will focus on the production and testing of the SRF cavities prior to installation into cryomodules. Specific attention will be given to the overall production cycle that is being implemented for this upgrade, the chemical processing that is being used along with the cavity performance that is being measured in the vertical testing dewars.

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PRODUCTION OVERVIEW

The 12 GeV upgrade, from the cavity production standpoint, began with the design and construction of several different prototype cavities which utilized low loss and high gradient cell shapes, and examined different aspects of thermal management, HOM damping and helium vessel design. From this effort an initial cavity processing cycle was developed which included the use of both buffer chemical polishing (BCP) as well as electropolishing (EP) to etch the inner surface of the cavities.[3] To the best of our knowledge this is the first production scale program that has adopted such a sequence, and with great results, which will be discussed below.

The final cavity processing cycle that is being used for the C100 program is shown in figure 1. This cycle is based on the prototype work mentioned before, in particular the R100 program, which was comprised of 8 cavities identical to the C100 cavities, but built in-house.

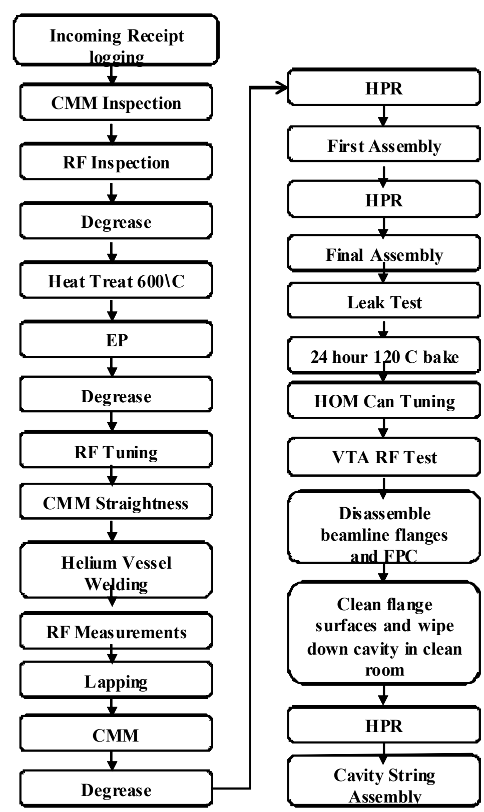

Figure 1: This is the process flow chart that is being followed for the C100 cavity production process for the 12 GeV upgrade.

This processing cycle has eliminated many of the redundant steps in an effort to reduce the cost and duration of the project. Some of the key items that make this process unique are the use of bulk buffer chemical polishing (BCP) material removal, performed by the cavity vendor, followed by a light electro-polishing (EP) cycle at JLAB. This progression allows us to take advantage of the benefits of both material removal processes, namely the faster and easier chemical etching provided by BCP along with the smoother surface provided by EP which allows cavities to achieve high accelerating gradient with very little Q slope.

In addition to the cost and time savings realized by having the cavity vendor carry out the BCP activity, there is also a significant reduction to the overall schedule duration as well as a reduction in the employees' exposure to the hazardous chemicals required for this work.

Another unique, and highly beneficial, feature of this processing cycle is the use of a single vertical RF test of the cavity, which is being done after it is welded into the helium vessel. The elimination of a vertical RF test before welding has helped to eliminate several months of processing time from the schedule, and was done after a 16 cavity comparison test was carried out with eight R100 cavities and eight C100 cavities. During this testing phase, cavity RF performance was measured before and after helium vessel welding. The maximum gradient achieved for these cavities before and after helium vessel welding is shown in figure 2. Two limitations exist which must be taken into account when examining the data. First, the cavities were subjected to a 27 MV/m administrative limit if the field emission was greater than 1 mSv/hr measured under the dewar lid. Second, the cavities are limited to 34 MV/m at 2.07 K when inside of the helium vessel due to the maximum heat exchange through the 82 mm helium vessel riser to the two-phase distribution header .

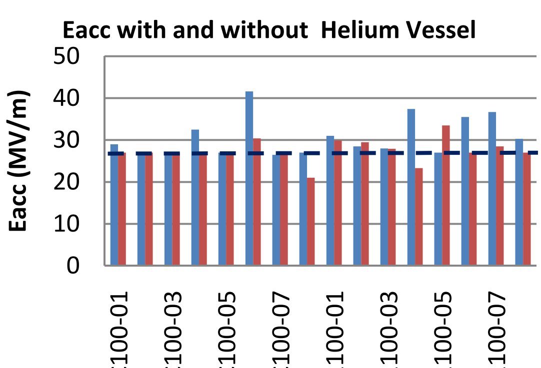

Figure 2: A comparison of 16 cavities' RF performance before (blue) and after (red) helium vessel welding. The administrative limit of 27 MV/m is shown by the dashed line. Note, the maximum gradient possible in a helium vessel is ~34 MV/m.

CHEMICAL PROCESSING

The upgrade cavities arrive from the vendor having received a 130 µm material removal from the inside of the cavity via BCP etch. Once at JLab, the cavities are given a light, 30 µm, EP prior to moving forward in the production cycle. The EP removal rate for our cavities is roughly 0.12 µm/min resulting in an average EP polish time of 4 hours. In order to help control the electrolyte temperature, an exterior cavity cooling system has been implemented that has proven very reliable and useful. A picture of the cavity in the EP tool can be seen in figure 3.

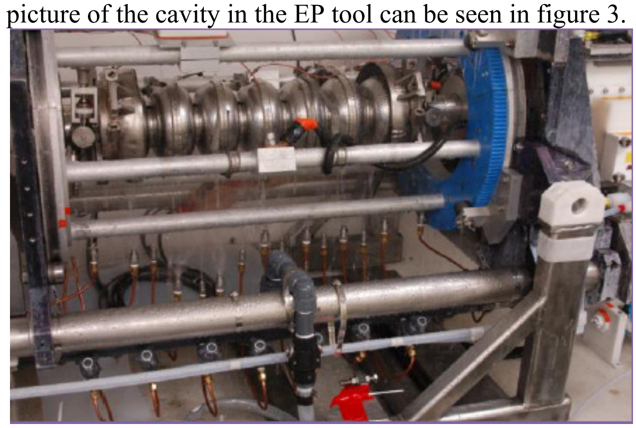

Figure 3: A 12 GeV upgrade cavity in the electropolishing tool. The spray cooling nozzles are shown at the bottom, and maintain the cavity at 20°C.

CAVITY RF PREPARATION

As our production cycle relies on a single RF test it also allows for the bulk of the associated RF tuning and measurements to be carried out once. Specifically, the RF frequency and field flatness tuning is done after the cavities have gone through their EP cycle, prior to helium vessel welding. Once the cavities are on frequency and the fundamental field is better than 95% field flat, the cavities helium vessels are welded on. This process is done in-house and allows for minimum turn-around time so that the cavities can continue towards the dewar for RF testing. Following the helium vessel welding, the cavity's RF field profile is re-measured, usually showing a slight degradation in field flatness associated with the handling and welding process itself. One lesson learned about the helium vessel welding was that the pre-welding target frequency needed to be set ~150 kHz above the desired final target frequency to account for the change in cavity frequency during the welding process.

Following the RF measurements, the cavity progresses towards vertical testing as outlined above, including passing through the CMM room to ensure the dimensional measurements are in tolerance and then into the cleanroom for the high pressure rinsing and assembly work to take place. Once the cavity is assembled it is leak checked and then baked at 120 C for 24 hours. The bake is only required once after EP, so for any repetitive testing this step is skipped. After the bake the higher order mode dampers are tuned to Qext $\geq 1e^{12}$ to ensure proper rejection of the fundamental mode, and the cables integrity is measured using a Time Domain Reflectometer (TDR). The latter became necessary as both the input power cables as well as our original rigid transmitted power and HOM cables were subject to an alarmingly high failure rate necessitating extra VTA cycles. The original rigid 0.141 "hard-line" cables, used for transmitted power and HOM cables, have since been replaced with flexible cables, and the failure rate has dropped to near zero.

CAVITY TESTING

After the cavities are installed in the dewar they are cooled down to 2.07 K, 29 Torr, for high power RF testing and higher order mode Q measurements. Testing at 2.07 K to reproduce the conditions the cavities will see in the cryomodule in the accelerator, and was chosen to save on the cryogenic cost associated with operating a large scale accelerator. To date, eight R100 cavities and thirty-six C100 Cavities have been vertically tested with only one cavity not meeting the design specification of 19.2 MV/m with a Qo >7.9e9. A summary of the C100 cavity testing performance is shown in figure 4, with a collection of 12 cavity tests Q vs. Eacc curves shown in figure 5. The Q vs. E curve demonstrates the excellent performance and minimal Q drop that is characteristic of the cavities being installed for the 12 GeV upgrade. It should be noted that there was an administrative limit applied at 27 MV/m during a large portion of these cavity tests as well, which limited our ability to measure the actual maximum performance of the cavities. This limit was applied to ensure the program was kept on schedule.

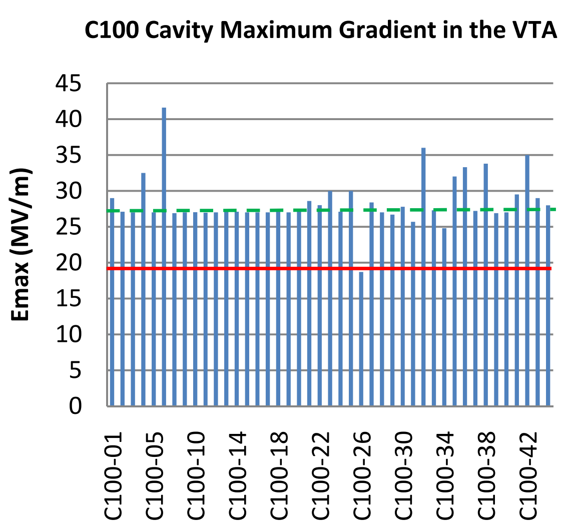

Figure 4: A summary of the C100 cavity testing performance as measured in the VTA. The dashed line shows the administrative limit of 27 MV/m, while the red line shows the design specification of 19.2 MV/m.

An additional RF measurement carried out in the VTA is the measurement of the higher order modes (HOM) in the cavity. Detailed modelling efforts have identified three dipole passbands between 1850 MHz and 3050 MHz that require a measurement of the loaded Q (Q_l) of each mode to ensure it is below the beam break up (BBU) threshold. The maximum allowable Q_l can be as low as $3x10^6$ for the band centered around 2880 MHz. In order to speed the analysis of these modes a pole fitting algorithm, Pole-fit, was developed to automate this process, and so far has resulted in 2-3 hours saved in manual computation per cavity.[4] In addition, to date only one cavity has been identified as having an HOM spectrum that is not within specification.

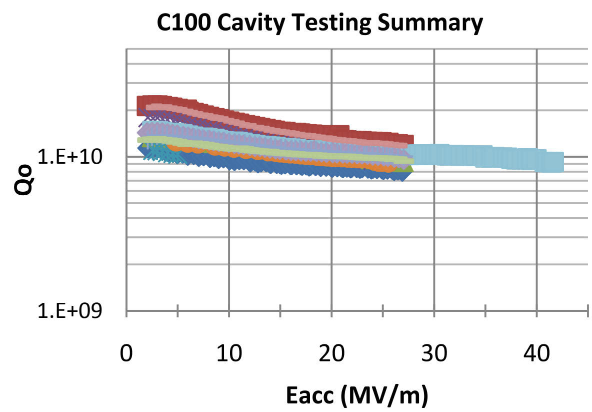

Figure 5: A sample of 12 C100 cavities RF performance demonstrating the excellent cavities that are being produced using the 12 GeV cavity processing cycle.

SUMMARY

The cavity processing and testing of 12 GeV upgrade cavities is on schedule and producing very high quality cavities that are greatly surpassing design specifications. To date all 86 cavities have been received from the vendor, 65 have been electropolished, 36 have been qualified in the VTA and 4 hermetic strings have been assembled and are moving towards being completed cryomodules. The plan over the coming 6 months is to build 6 more hermetic strings for cryomodule construction testing and installation into CEBAF in 2013.

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