SRF CAVITY PERFORMANCE OVERVIEW FOR THE 12 GEV UPGRADE*

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Abstract

The CEBAF accelerator, a recirculating CW electron accelerator that is currently operating at Jefferson Laboratory, is undergoing a major upgrade to increase the maximum beam energy from 6 GeV to 12 GeV. One of the key components of this upgrade is the installation of 10 new cryomodules containing 80 seven-cell elliptical superconducting RF (SRF) cavities.[1] The fabrication, processing and RF qualification of these cavities was completed in February 2012[2] and the cavity performance achieved during vertical RF testing at 2.07 K has exceeded the design specification by ~25%, a testament to the cavity design and processing cycle that has been implemented. This paper will provide a summary of the cavity RF performance in the vertical tests, as well as review the overall cavity processing cycle for the project.

INTRODUCTION

The 12 GeV upgrade to the CEBAF accelerator, currently operating at 6 GeV, is a large scale project that requires the installation of several key components to allow for the machine to operate at the increased energy.[3] This includes the installation of an additional arc to the accelerator, the installation of a new transport beam line and a new experimental hall, Hall D, the upgrade of the magnets and power supplies for the complex, the more than doubling of the cryogenic capacity of the central helium liquefier (CHL) and the installation of 10 new cryomodules and associated RF zones. The SRF cavities that make up these 10 cryomodule are the focus of this paper.

In order to double the energy of the CEBAF accelerator, 10 new C100 cryomodules each containing 8 SRF cavities will be installed. (The term C100 refers to the ~100 MeV energy gain in each cryomodule compared to the 20 MeV energy gain in the original C20 CEBAF cryomodules that were installed in the early 1990s).[4] To date, all of the cavities for these cryomodules have been tested and all of the hermetic cavity string assemblies have been completed. This paper will focus on the processing and RF testing of the SRF cavities prior to assembly into hermetic strings.

PROCESS FLOW OVERVIEW

The steps necessary to prepare a cavity for installation in a string are a combination of cavity metrology, RF measurements, mechanical attachments, and chemical processing of the interior RF surface of the cavity. As each of these steps has some influence on the other steps it is critical to arrive at the appropriate cavity processing cycle that will ensure a successful acceptance RF test, the final measurement before string assembly. For the C100 program, great efforts when into refining the final cavity process flow, shown in Figure 1.

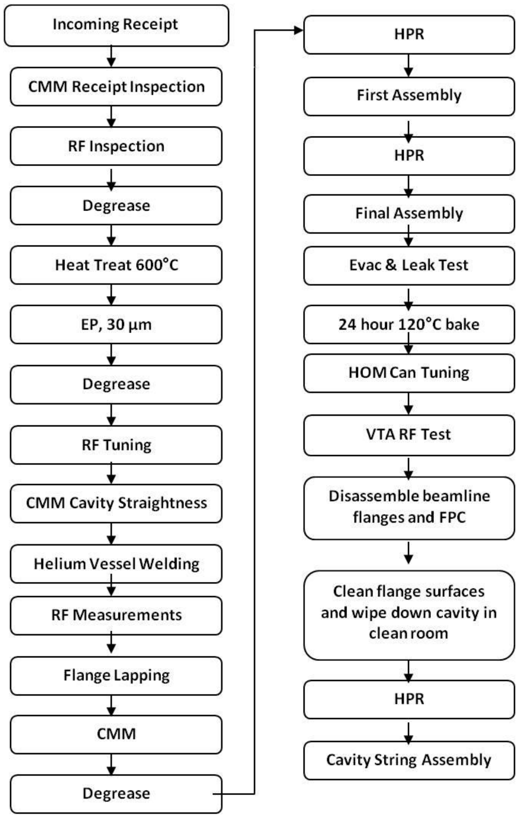

Figure 1. Process flow chart showing all of the cavity processing steps for the C100 cavity production program.

Through an improved understanding of the cavities themselves, and the influence of each process on the cavity, it was possible to eliminate a number of steps that were previously performed for projects such as the original CEBAF construction and the C50 CEBAF upgrade.[5] In order to ensure a complete understanding of each step, prior to determining if it could be removed, a detailed study was carried out on 8 C100-style prototype cavities that were fabricated in-house, termed R100

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cavities, as well as 4 of the C100 cavities, supplied by an outside vendor. More background information on the process steps that have been eliminated after a detailed study can be found in reference 6 and will be briefly reviewed below.[6]

The first key items that make this processing cycle unique, as well as very efficient, is the use of a bulk, 150 µm, buffered chemical polishing (BCP) etch of the interior of the cavity combined with a light, 30 µm, electropolishing (EP), prior to RF testing in the vertical testing area or VTA. In order to help streamline the process, the bulk BCP was carried out by the vendor prior to shipping the cavities to JLab. This provided a significant time and cost savings to the project and allowed us to focus on the other cavity processing steps.

By combining BCP with EP it is possible to take advantage of the speed and reduced complexity of BCP for the bulk material removal along with the improved surface finish and associated improvement in cavity performance associated with EP.[7, 8] The EP process helps provide a more uniform, smoother RF surface reducing the amount of Q slope exhibited during cavity testing. The corresponding reduction in power dissipated into the cavity translates into potential significant savings in utility costs to operate the accelerator. Furthermore, this is the first large scale project to utilize the combined BCP/EP cavity processing cycle and has done so with great success as demonstrated in the next section.

Confidence in process control enabled the elimination of cavity testing prior to welding the helium vessel onto each cavity. This made it possible to eliminate 11 steps from the process cycle that required 2 VTA tests.[6] The elimination of the extra RF test eliminated several months of processing time from the schedule resulting in significant cost savings.

CAVITY TEST RESULTS

For the C100 program 86 cavities were procured of which 80 were required for use in the upgrade cryomodules. In order for a cavity to be considered as “qualified” for installation into a cryomodule it had to meet several cavity performance criteria, including meeting accelerating gradient and Qo specifications, being better than 95% field flat in the fundamental mode and having adequately damped higher order modes (HOMs) to avoid beam break up (BBU) in the accelerator.[9] A thorough review of the cavity testing process can be found in reference 10.[10]

A key metric for the C100 SRF cavities is the maximum accelerating gradient achieved in the VTA for cavities inside of the helium vessel, a plot of which is shown in Figure 2. On the plot there are two solid horizontal lines, one corresponding to the 12 GeV project specification, achieving > 19.2 MV/m at a Qo > $7.2e^9$ when tested at 2.07 K (29 Torr), while the second is the administrative limit on the maximum gradient to which cavities could be tested in the VTA during most of the production run. This administrative limit was put in place to avoid excessive re-testing associated with having an undesirable event occur at high gradient that could cause an otherwise qualified cavity to no longer meet the project specification. It should be noted from this graph that there was only 1 cavity that did not meet the 12 GeV gradient specification and only 11 failed to reach the administrative limit.

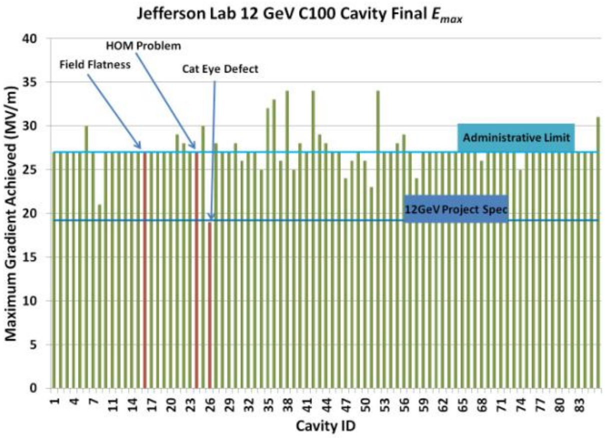

Figure 2. A summary of the C100 cavity performance in the VTA is presented for all 86 cavities that were fabricated and tested.

Overall, there were 3 cavities that were not qualified to be installed into a cryomodule, one due to a defect on an equator weld (cat eye defect), one that did not meet the HOM specification and one that was too far outside of our field flatness specification to be used. Thus, 96% of the cavities met the requirements for use in a C100 cryomodule.

Another important aspect of any production activity is the amount of re-processing required to achieve a satisfactory result. A cavity was considered to require reprocessing if it did not meet the Q vs E specification described above, or if it was producing more than ~ 10 mSv/hr of gamma radiation at 19.2 MV/m. Although the latter was not part of the written procedure, it was the widely implemented rule, which should be formally included in future projects. A summary of this data can be seen in Figure 3.

One of the items to note is that half of the cavities that required re-processing had a cold leak, meaning the cavity was leak tight at room temperature however upon cooldown to 2.07K the cavity began to leak. In these instances if the vacuum pressure, as measure on the top plate of the test stand, was greater than $1e^{-6}$ Torr the test was aborted.

An important fact to take away from Figure 3 is that only one of the cavities that was reprocessed needed an additional EP cycle, and only 15 µm of material were removed in this case to recover from an inadvertent HPR wand strike. The balance of the cavities were recovered by high pressure rinse (HPR) only.

As mentioned above, the amount of radiation a cavity produces during VTA testing is of concern since increased amounts of field emitted electrons can be detrimental to accelerator operations once the cavities are installed in the machine. Fortunately, it was often found that the C100 cavities' field emission level, in the VTA, would decrease after a variety of RF processing techniques were applied, including operation in the pass-band modes.

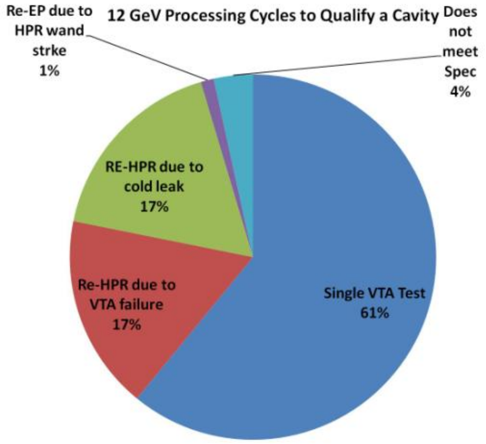

Figure 3. This pie chart shows the number of cavities that met the 12 GeV specifications on the first pass, and which ones required additional processing steps to meet the specification.

A summary of the radiation measurements taken in the VTA at an accelerating gradient of 20 MV/m for both the initial power rise and following all RF processing, the final power rise is shown in Figure 4. This chart is for the final acceptance test in the VTA. On the chart there are also two lines denoting the average peak radiation values for the first power rise as well as the final power rise, both measured at 20 MV/m. It can be seen that there is almost a one order of magnitude decrease in radiation between the initial and final power rise, resulting in an average radiation level of 190 µSv/hr at 20 MV/m as measured at the top plate of the test stand insert ~ 2 meters away from the top end of the cavity.

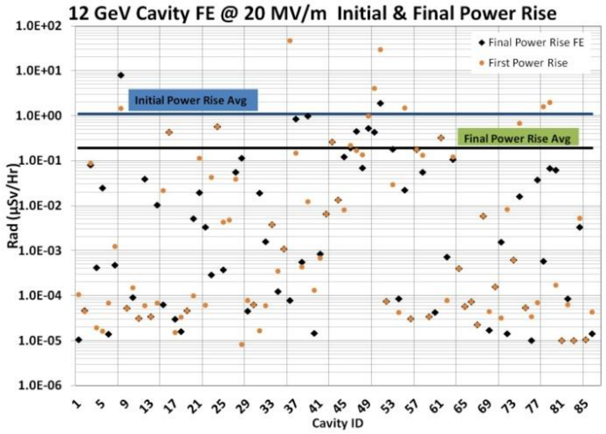

Figure 4. The radiation level measured inside the dewar lid for each of the 12 GeV cavities while operating at 20 MV/m. The graph shows data for both the initial and final power rise.

One of the items of interest during VTA testing is the field emission onset threshold, which is the gradient at which the observed radiation level exceeds background levels (0.1 µSv/hr). From the final power rise data shown in Figure 4 it can be seen that 35% of the cavities were below the field emission onset threshold at 20 MV/m.

SUMMARY

The cavity processing and testing of 12 GeV upgrade cavities has been completed and all 10 hermetic strings assembled. 96% of the cavities for the project met the program specifications, and 61% met this specification with a single cold RF test. The average radiation level at the operating gradient was 190 µSv/hr, which if maintained in the cryomodule should introduce very little additional heat into the cryogenic system.

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