

# OVERVIEW AND LESSONS LEARNED OF THE JEFFERSON LAB CRYOMODULE PRODUCTION FOR THE CEBAF 12GEV UPGRADE\*

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## Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is nearing completion of an energy upgrade from 6 to 12 GeV. An integral part of the upgrade is the addition of ten new cryomodules, each consisting of eight seven-cell superconducting radio-frequency (SRF) cavities. An average performance of 100+MV of acceleration per cryomodule is needed to achieve the 12 GeV beam energy goal. The production methodology was for industry to provide and deliver the major components to Jefferson Lab, where they were tested and assembled into cryomodules. The production process begins with an inspection upon receiving of all major components followed by individual performance qualification testing. The SRF cavities received their final chemical processing and cleaning at Jefferson Lab. The qualified components along with all associated hardware and instrumentation are assembled, tested, installed into CEBAF and run through an integrated system checkout in preparation for beam operations. The production process is complete and one of the first completed cryomodules has successfully produced 108 MV of acceleration with a linac beam current of 465  $\mu$ A.

## INTRODUCTION

The ten C100 cryomodules accounted for approximately one-quarter of the accelerator budget and 10% of the total budget for the 12 GeV upgrade project. The scope of the cryomodule production run consisted of the design, procurement, assembly, acceptance testing and a final integrated performance checkout with all associated CEBAF operating systems. The first superconducting radio frequency (SRF) niobium cavities were delivered in 2010. These SRF cavities were individually qualified in vertical dewars [1] at Jefferson Lab. In 2011, (ahead of the baseline schedule) the first two production 12GeV-C100 cryomodules were installed and commissioned in the CEBAF machine. These first two cryomodules accelerated and delivered beam for six months of physics experiments. In May 2012, one of the 12GeV-C100 cryomodules was successfully operated at a total energy of 108MV (with a linac current of 465uA) while delivering three-pass beam to the experimental halls [2]. This beam loaded performance demonstrated the design and production process of the C100 cryomodules would meet the 12 GeV requirements.

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## DESIGN

The original CEBAF cryomodule design consists of 8-five-cell cavities and produces a nominal voltage of 20 MV per cryomodule. 40 cryomodules (20/linac) were installed in the original CEBAF and produced enough voltage to run the machine at 4GeV. Over time the performance of these cryomodules was improved and optimized to increase CEBAF operation to 6GeV. The C100 cryomodule design consists of 8-seven-cell cavities and produces 100 MV per cryomodule (500 MV/linac). By adding the ten new C100 cryomodules and an additional 1/2-pass (tenth arc) to the existing accelerator, the maximum operating energy of CEBAF will be doubled from 6GeV to 12GeV.

## Parameters

The C100 cryomodule design was developed over several years and is based on a set of early developmental cryomodules designed, built and operated in the Jefferson Lab CEBAF and FEL accelerators. The C100 cryomodule design parameters (see Table 1) were developed in concert with the other associated 12GeV accelerator system upgrades [3]; including the 4.6kW (at 2K) Central Helium Liquefier (CHL) [4], High power (13kW) radio-frequency klystrons (HPRF) and a new digital low-level radio-frequency (LLRF) control system [2].

Table 1: C100 Design Specifications

Parameter	Design Specification	Units
Slot length (includes warm section)	9.8	Meters (m)
Voltage/Cryomodule	108	MeV
2K heat load	<300	Watts
50K heat load	<300	Watts
HOM Damping (transverse)	<2.4x10 <sup>10</sup>	Ohms/meter
HOM Damping (longitudinal)	<6.5x10 <sup>11</sup>	Ohms
Cavity Gradient	19.2	MeV/m
Qo (@19.2 MV/m)	7.2E9	N/A

To meet the 12 GeV performance criteria, each of the ten cryomodules will need to provide 98 MeV of energy. In order to provide performance margin, the cryomodule is designed to produce 108 MeV. This additional performance capability provides the option to run some cryomodules higher in voltage in the event that more energy is needed to make up for lesser performing cryomodules. Similarly, the SRF niobium cavities were

individually qualified at 19.2MV/m even though they only need to provide 17.5MV/m to meet the baseline performance. Subsequently, all of the cryomodule power related components (power couplers, cooling circuits, RF-windows, etc.) were also designed and specified to operate 10% above the baseline performance requirements.

### Focused Areas of Design & Performance

The damping of higher order modes (HOM) in SRF cavities is a critical design parameter for recirculating accelerators. To mitigate against the possibility of having beam break-up (BBU) in the CEBAF accelerator an extensive effort was put into the measuring and characterizing the HOM spectrum of each cavity before it was built into a cryomodule [5]. Custom end-groups, that mimicked the boundary conditions the cavities would experience when assembled into a cryomodule, were designed and attached to each cavity during vertical testing (see Figure 1). These purpose built test end-groups allowed the HOM spectrum of each cavity to be characterized (and qualified) prior to being released for assembly into a cryomodule.

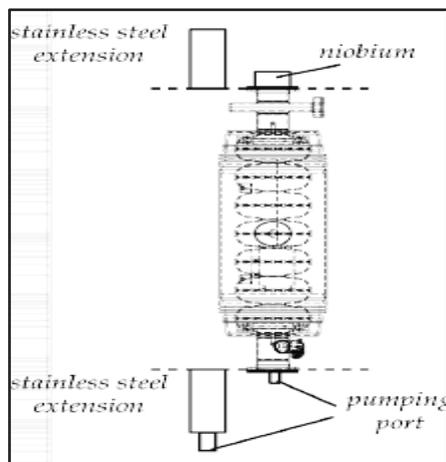


Figure 1: Custom SS end-groups assembled onto cavity during vertical testing.

The microphonic response of the SRF cavities to their environment is another design area that needed very careful attention. Excessive microphonic vibration creates dynamic detuning in the cavity and requires additional RF-power to keep the cavity on frequency with the power and control systems. In preparation for the 12 GeV project, a horizontal test bed (HTB) was assembled with two C100 cavities, helium vessels and tuners to investigate the microphonic response of the design. Results from this test demonstrated the design met the requirements.

Subsequently, the microphonic response was measured on the first production C100 cryomodule during final acceptance testing. Results from this acceptance test showed a higher than anticipated microphonic response. Upon further investigation, it was discovered the boundary conditions of the HTB did not fully represent the 'real' conditions of the C100 cryomodule. In response

to these results, the tuner design was modified to reduce the microphonic response of the cavity/tuner system [6]. This cavity/tuner interface redesign was implemented on the final seven (of ten) cryomodules (see Figure 2).

At the point of implementation, production on the first three cryomodules had progressed beyond the point where the cavity/tuner interface could be retrofitted with the redesigned parts. Piezo elements will be used on these first three production units to minimize the additional detuning burden on the LLRF system.

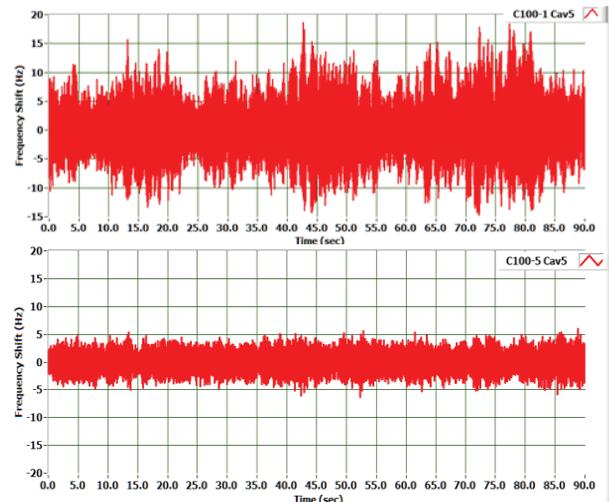


Figure 2: Microphonic detuning - Original design (top), redesigned (bottom) cavity/tuner system.

## PRODUCTION

Cryomodule production began with the receiving inspections of the individual components that had been procured from industry. All components have established acceptance criteria that must be satisfied before components are released for use in cryomodule production. These receiving inspection criteria vary from simple visual inspections to multiple qualification processes including mandatory hold points for independent quality assurance.

The cavity qualification process was the first step in cryomodule production. Each C100 cavity was individually qualified after helium vessel welding in the Jefferson Lab SRF vertical test area (VTA). Each cavity was put through a standardized set of tests to verify the project performance parameters were met [7]. Each cavity must produce on average, 17.5 MV/m to meet the baseline performance goal of the 12 GeV project. To provide operational contingency, each cavity was qualified to 19.2 MV/m with a  $Q_0$  of 7.2E9.

An administrative limit of 27 MV/m was periodically implemented on cavity qualification testing in order to reduce the risk of potentially degrading cavity performance and the need to re-test cavities (see Figure 3). Only one cavity (out of 86) failed to meet the gradient qualification goal of 19.2 MV/m. Two additional cavities were disqualified for use in production due to failure to meet the HOM damping and field flatness specifications.

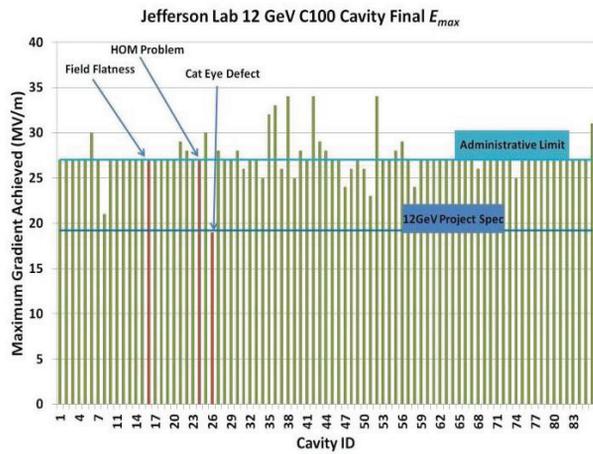


Figure 3: C100 cavity qualification in the VTA.

Once eight cavities were qualified for use in cryomodule production, they were assembled into a hermetically sealed cavity-string in a class 100 cleanroom (see Figure 4). The cavity string assembly was then moved to the cryomodule assembly area where the cold mass structure was constructed. Cold mass assembly includes the cold magnetic shielding (CRYOPERM), 2K helium piping, cold tuner section, instrumentation and multi-layer insulation (MLI).



Figure 4: Cavity string assembly in Class 100 cleanroom.

The cold mass assembly was then transferred to the space frame support structure with an integrated 50K thermal shield and MLI. The cavity string was then concentrically aligned to within 0.5mm. The final assembly consists of installing the vacuum vessel, cryogenic end cans, warm tuner sections and the waveguide fundamental power coupler assemblies. Once the cryomodule assembly was complete, a final QC check was performed to verify the mechanical, electrical and vacuum systems were functioning properly in preparation of final acceptance testing.

## PERFORMANCE

### Acceptance Testing

Each C100 cryomodule went through a final acceptance testing process in the Test Lab Cryomodule Testing Facility (CMTF) prior to being installed in the CEBAF machine. Acceptance testing is an operational checkout of the cavity performance and all of the cryomodule subsystems. Once all the cryogenic connections and control read-backs have been checked out, the C100 cryomodules were able to be slowly (10-20K/hr) cooled down from 300K to 4K without any degradation in performance due to Q-disease. This slow cooldown reduces the risk of creating a vacuum leak and allows for a lower temperature gradient within the cryomodule, thereby reducing the mechanical stresses associated with cooldown. Once the cryomodule was cooled to 4K, it was then pumped down to 2K for high power acceptance testing. Along with verifying all associated power and control signals were functioning properly, all the cryomodule operational parameters were measured for compliance with the design specifications.

High power RF was applied to each cavity to determine its maximum gradient (restricted only by an administrative limit of 25MV/m) while measuring the corresponding heat load ( $Q_0$ ). In addition, all the other operational systems such as tuners, HOM damping, cryogenic valves and instrumentation were qualified. One limitation is that high power can only be run into one cavity at a time. Therefore, the full cryomodule voltage must be estimated when based on acceptance testing results. With over twenty years of experience, these estimates have proven to be reliable for predicting operation in the tunnel.

Following final acceptance testing, the cryomodules were moved from the CMTF to the CEBAF tunnel for installation and commissioning. The installation process involves connecting the cryomodule to the cryogenic, RF-power, beamline vacuum and operational safety systems. Once all connections were complete and control signal read-backs have been verified, the cryomodule was again slow cooled to 4K, pumped down to 2K and refilled in preparation for the final integrated operational checkout and commissioning process [8].

As was done during acceptance testing, all the operational subsystems were checked out for proper function and the critical accelerating parameters were measured. To date 9 (of 10) of the C100 cryomodules have completed the commissioning process (see Table 2). The in-tunnel performances of all these cryomodules have exceeded the baseline required for 12 GeV operations. Two cryomodules did not achieved the design goal of 108 MV/m, however there is still more than adequate margin in the ensemble performance to meet the program goals.

Table 2: C100 Commissioning Results

Cryomodule No.	Commission in CEBAF (MeV)	Operation with Beam (MeV)
C100-01	104.3	94.5
C100-02	109.6	108
C100-03	118.4	Jan 2014
C100-04	105.8	Jan 2014
C100-05	109.9	Jan 2014
C100-06	108.2	Jan 2014
C100-07	108.4	Jan 2014
C100-08	Oct 2013	Jan 2014
C100-09	113.7	Jan 2014
C100-10	109.8	Jan 2014

### Gradient with Beam Loading

As stated above, the first two C100 production cryomodules were installed into the CEBAF machine in the fall of 2011. They were run with beam for the full six month physics run. This runtime was very beneficial with regard to gaining real operational experience running the C100 cryomodules while delivering physics quality beam to the experimental halls [2]. During beam studies time, the gradients on the C100 cryomodules were pushed up in order to test the performance of the entire ‘vertical slice’ (cryomodule, cryogenics, rf-power, digital LLRF controls, etc.) of the accelerating zone.

During one of these beam studies opportunities, C100-02 was operated at a maximum voltage of 108 MV while delivering multi-pass beam to the experimental halls. Having successfully demonstrated this capability early in the 12 GeV project was very encouraging for the future operations of the CEBAF machine.

### Cost

From a cost standpoint, cryomodule production is >99% complete. For the purpose of this paper, the final 12 GeV cryomodule costs are broken down into three categories; procurements, expenses and labor (see Figure 5). These costs include all activities from the initial procurement process through assembly, acceptance testing, installation and commissioning.

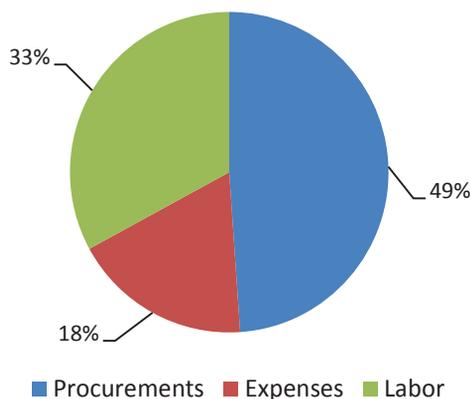


Figure 5: Cryomodule cost breakdown.

The procurement costs are the expenditures associated with the vendor subcontracts for the major cryomodule components such as the SRF-cavities, thermal & magnetic shields, tuners, helium vessels, space-frames, vacuum vessels and cryogenic end cans. The expenses category includes all ‘other’ production costs such as consumables, minor procurements and travel to vendor sites. The labor costs include the labor associated with all cryomodule production activities from individual component QA receiving activities through assembly, installation and commissioning activities.

In order to better understand the level of effort that goes into cryomodule production activities, the labor costs are further broken down (see Figure 6). The labor breakdown shows that quality assurance accounts for approximately one-third of the total labor costs. These QA processes include the labor needed to create the procedures, perform the individual component receiving inspections, document the results and maintain the project database system.

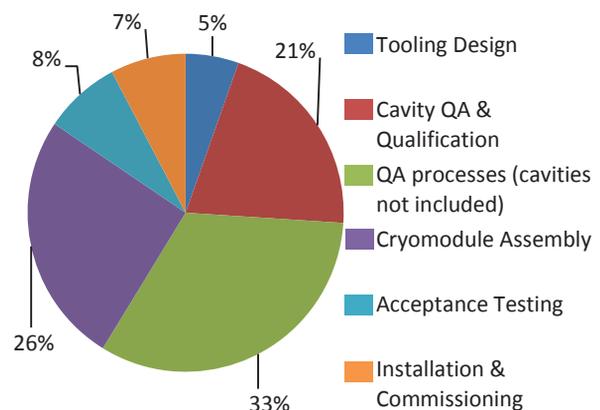


Figure 6: Cryomodule labor breakdown.

Cavity QA and qualification activities account for about one-fifth of the total labor costs. Each of the eighty-six cavities went through a thorough receiving inspection that includes both a dimensional check on a coordinate measurement machine (CMM) and an RF-check to verify that the cavity frequency and field flatness were within specification. Once accepted, the cavities were then run through final processing in preparation for qualification in the VTA. Vertical testing is a time consuming and expensive process, minimizing these testing cycles reduces both project cost and schedule. For this reason, a focused effort was dedicated to process control for cavity qualification. This forethought and planning effort resulted in minimal retests for qualification (see Figure 7). 65% of all the C100 cavities were qualified on the first test cycle.

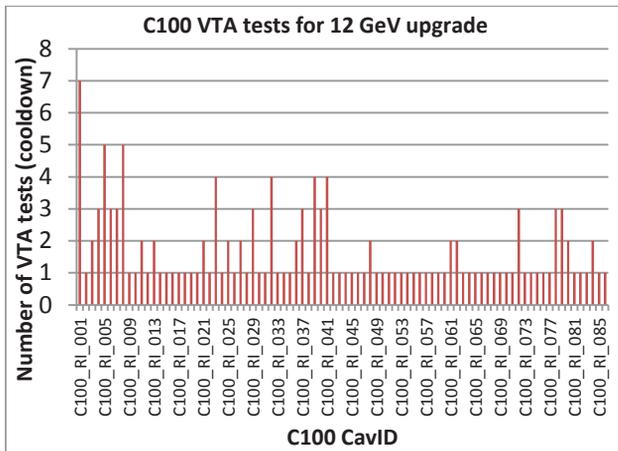


Figure 7: Cavity qualification test cycles in VTA.

Cryomodule assembly accounts for about one-quarter of the total labor costs. As stated above, the cryomodule assembly activities begin with the transfer of the cavity string from the cleanroom and run through final instrumentation checkout and leak check of the insulating vacuum (see Figure 8). There is a significant amount of skilled touch labor involved in these processes. The importance of the skilled staff to the success of this project cannot be understated; for this reason these resources need to be optimized. As with cavity qualification, a focused planning effort was dedicated to optimizing assembly activities and procedures to be efficient without compromising quality.



Figure 8: Cryomodule production group w/ C100-07&-08.

## CONCLUSION

At the time this paper was written (Sep 2013), the 12 GeV-C100 cryomodule production run is virtually complete. All ten C100 cryomodules have been assembled, tested and installed in the CEBAF tunnel. Nine have completed their final integrated checkout and commissioning. The last cryomodule is scheduled to complete commissioning in October 2013.

CEBAF operations are scheduled to begin hot-checkout in November 2013. During this process all ten C100 cryomodules will be calibrated with the electron beam in preparation for 12 GeV physics. The lessons learned from the CEBAF 12 GeV Upgrade cryomodule production run include the importance of planning, prototyping, monitoring of performance throughout production and the clear definition of all acceptance criteria.

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