12 GeV UPGRADE PROJECT – CRYOMODULE PRODUCTION *

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Abstract

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) is producing ten 100+MeV SRF cryomodules (C100) as part of the CEBAF 12 GeV Upgrade Project. Once installed, these cryomodules will become part of an integrated accelerator system upgrade that will result in doubling the energy of the CEBAF machine from 6 to 12 GeV. This paper will present a complete overview of the C100 cryomodule production process. The C100 cryomodule was designed to have the major components procured from private industry and assembled together at Jefferson Lab. In addition to measuring the integrated component performance, the performance of the individual components is verified prior to being released for production and assembly into a cryomodule. Following a comprehensive cold Acceptance Test of all subsystems, the completed C100 cryomodules are installed and commissioned in the CEBAF machine in preparation of accelerator operations. This overview of the cryomodule production process will include all principal performance measurements, acceptance criterion and up to date status of current activities.

INTRODUCTION

The cryomodule portion of the 12 GeV upgrade project began with the conceptual design phase in 2001. The design was finalized and component procurements began in 2009. In 2010, the first superconducting radio frequency (SRF) niobium cavities were individually qualified in vertical dewars [1] at Jefferson Lab. In 2011, ahead of the baseline schedule, two cryomodules were installed and commissioned in the CEBAF machine. These first two C100 production cryomodules have been accelerating and delivering beam for six months of physics experiments. During this physics run, gradients were opportunistically increased in one of the 12GeV cryomodules to a total energy of 108MV (with a linac current of 465uA) while delivering three-pass beam to the experimental halls. This beam loaded performance demonstrates that the design and production process of the C100 cryomodules will meet the 12 GeV requirements.

DESIGN

When the original CEBAF machine was completed, there were ten (5 in each linac) empty accelerating zones available for a future energy upgrade. Therefore, the design length of the 12 GeV C100 cryomodule was limited to ensure it would fit in the existing tunnel infrastructure. The 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 machines. The C100 cryomodule design parameters (see Table 1) are also consistent with other 12 GeV accelerator system upgrades including the 4.6kW (at 2K) refrigerator, 13kW klystrons and new digital low-level radio-frequency (LLRF) control system.

Parameters

To meet the 12 GeV performance criterion, each of the ten cryomodules will need to provide 98 MeV of energy. In order to provide performance margin, the cryomodule is designed to be operated at 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.

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)	$<2.4\text{x}10^{10}$	Ohms/meter
HOM Damping (longitudinal)	$<6.5\text{x}10^{11}$	Ohms
Cavity Gradient	19.2	MeV/m

Similarly, the SRF cavities were individually qualified at 19.2MV/m even though they only need to provide 17.5MV/m to meet the baseline requirements. All of the power related components (power couplers, cooling circuits, rf-windows, etc.) were designed and specified to operate 10% above the baseline performance requirement.

Infrastructure Integration

As stated above, the C100 cryomodules will be installed and operated in the existing CEBAF machine. All operational systems such as safety, cryogenics, rf-power, instrumentation and controls must be designed to interface with existing infrastructure.

Following the precedent set by the production of the previous CEBAF cryomodules; the 12GeV C100 cryomodules are designed to have the primary

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components procured from industry and then received, qualified and assembled at Jefferson Lab. In addition, the design needs to interface with specialized tooling that already exists for handling, assembling, transporting and installing completed cryomodules.

PRODUCTION

Cryomodule production begins with the receiving inspections of the individual components that have been procured from industry. This is the initial ‘hands-on’ portion of the quality assurance (QA) process. All components have established acceptance criteria that must be satisfied before components are released for use in production.

Cost

From a cost standpoint, cryomodule production is >90% complete. For the purpose of this paper, the final 12 GeV cryomodule costs are projected and broken down into three categories; procurements, expenses and labor (see Fig 1). These costs include all activities from the solicitation of procurement proposals through assembly, installation and commissioning.

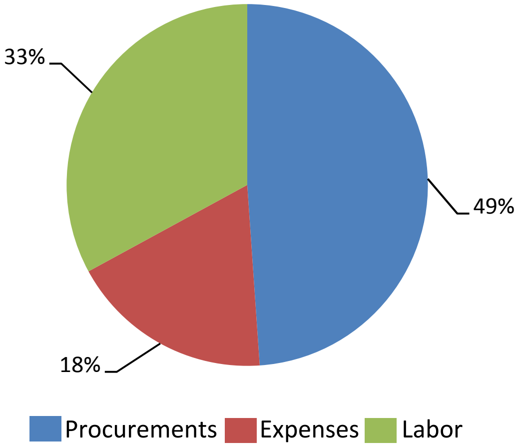

Figure 1: Cryomodule cost breakdown – Projected.

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 Fig 2). 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 database system.

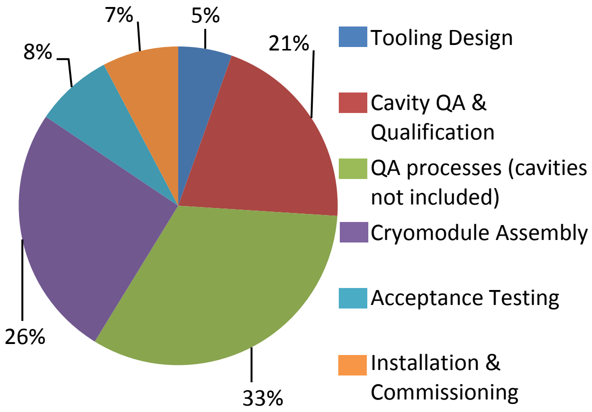

Figure 2: Cryomodule labor breakdown.

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 Vertical Test Area (VTA). Each cavity is qualified [2] at 2K to verify gradient and Qo performance and HOM damping [3] prior to being released for production. Once eight cavities have been qualified they are assembled (within a class-100 cleanroom) into a single hermetically sealed cavity string. (see Fig 3.)

Figure 3: C100 cavity string in Class-100 cleanroom.

Cryomodule assembly accounts for about one-quarter of the total labor costs. The cryomodule assembly activities begin with the transfer of the cavity string from the cleanroom. From this point the assembly progresses through the cold mass, installation of instrumentation, cavity alignment, through final instrumentation checkout and leak check of the insulating vacuum.

Schedule

At the time this paper was written (May 2012), six of the ten 12 GeV C100 cryomodules have been completely assembled. Five cryomodules have completed acceptance (results below) and two have been installed and commissioned in the CEBAF machine. Assembly of the seventh & eighth cryomodules is currently in progress (see fig 4). The assembly of the last cryomodule is on schedule to be complete by the end of this calendar year.

The CEBAF machine is scheduled to enter a long maintenance period beginning in May 2012. During this long maintenance period, the remaining eight C100 cryomodules will be installed and commissioned in preparation for 12 GeV physics.

PERFORMANCE

Acceptance Testing

Each C100 cryomodule goes through an acceptance testing process in the Test Lab Cryomodule Testing Facility (CMTF) prior to being installed in the CEBAF machine (see Table 2.). Acceptance testing is an operational checkout of all the cryomodule subsystems. This testing entails cooling both the shield and primary circuits down to their nominal operating temperatures of 50K and 2K respectively. Each cavity is powered individually to determine its maximum gradient while measuring the corresponding heat load (Qo). In addition, all the other operational systems such as tuners, HOM dampers, valves and instrumentation are 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 accurate.

Table 2: C100 Acceptance Testing Results

Cryomodule No.	**Design Specification (MeV)**	**Testing Result (MeV)**
C100-01	108	104
C100-02	108	108* (*with beam loading)
C100-03	108	114
C100-04	108	113
C100-05	108	112

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 have been running with beam for the last six months. This runtime has been very beneficial [4] with regard to gaining real operational experience running the C100 cryomodules while delivering physics quality beam to the experimental halls. During beam studies time, the C100 cryomodules gradients were pushed up in order to test the performance of the entire 'vertical slice' (cryomodule, cryogenics, rf-power, digital LLRF controls, etc.).

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. Being able to demonstrate this capability at this point in the 12 GeV project is very encouraging for the future operations of the CEBAF machine.

Figure 4. Cryomodule production group w/ C100-07&-08.

REFERENCES

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