# PERFORMANCE OF THE FIRST C100 CRYOMODULES FOR THE CEBAF 12 GeV UPGRADE PROJECT*

M. Drury, A. Burrill, G. K. Davis, J. Hogan, L. King, F. Marhauser, H. Park, J. Preble, C. E. Reece, R. Rimmer, A. Reilly, H. Wang, and M. Wiseman,
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606 USA

## *Abstract*

The Thomas Jefferson National Accelerator Facility is currently engaged in the 12 GeV Upgrade Project. The goal of the 12 GeV Upgrade is a doubling of the available beam energy of CEBAF from 6 GeV to 12 GeV. This increase in beam energy will be due primarily to the construction and installation of ten "C100" cryomodules in the CEBAF linacs. The C100 cryomodules are designed to deliver an average 108 MV each from strings of eight seven-cell, electropolished, superconducting RF cavities operating at an average accelerating gradient of 19.2 MV/m. The new cryomodules fit in the same available linac space as the original CEBAF 20 MV cryomodules. Cryomodule production started in September 2010. Initial Acceptance Testing started in June 2011. Four C100 cryomodules were installed and tested from August 2011 through July 2012. The first two of these cryomodules were successfully operated during the last period of the CEBAF 6 GeV era, which ended in May 2012. This paper will present the results of Acceptance Testing and Commissioning of the C100 style cryomodules to date.

## INTRODUCTION

Since July 2011, six C100 cryomodules have been delivered to the Cryomodule Test Facility (CMTF) for Acceptance Testing. Four of these cryomodules have been installed in the South Linac of CEBAF and commissioned. Two of these, C100-1 and C100-2, have been operated with beam during the final 6 GeV operations period for CEBAF which started in November 2011 and ended in May 2012.

Each cryomodule goes through two testing cycles, acceptance testing prior to installation in the linac and a final commissioning after installation.

Acceptance testing is generally a more comprehensive set of tests than the final commissioning and is meant to uncover any major problems before delivery to the linac. An example of such a problem would be the failure of an instrumentation feedthru during cooldown that leads to the loss of insulating vacuum. Such problems are more easily addressed while the cryomodule is in the CMTF.

During acceptance testing, each cavity is tested to insure proper operation of the mechanical and piezo tuners. Low power measurements using a network analyser are made to characterize the seven passbands of each cavity once the cavities have been tuned to 1497.000 MHz. The higher order modes of each cavity are also characterized at low power. Each cavity is then characterized in terms of maximum gradient, field emission, and unloaded $Q$ ($Q_0$). Measurements of microphonics, pressure sensitivity, static Lorentz coefficients and static heat loads are also conducted.

Once the cryomodule has been installed in a linac, it is commissioned. Commissioning consists of a subset of the acceptance tests. The focus for commissioning is determining stable operating gradients, measuring field emitted x-ray production, $Q_0$ and microphonics.

## MICROPHONICS

The measurement of cavity detuning due to external vibration sources is conducted in both the CMTF and in the tunnel. The results of these measurements, however, are location and time dependent. We now know that the CMTF has a large number of vibration sources that are not present in the tunnel environment. This paper will focus on measurements made on installed cryomodules.

A maximum peak detuning of 25 Hz was budgeted for the C100 cavities. Microphonics testing of the first unit (C100-1) met design goals, but results were higher than expected based on prototype testing. C100-1 as measured during operation in the CEBAF tunnel ranged as high as 21 Hz peak detuning during a 500 second sample time period [1]. While within the specification, the results were higher than predicted. These results led to a modification of the mechanical tuner system in order to gain margin. The tuner modification was first installed on the cavities in C100-4. Thicker plates at either end of the tuning structure led to an average reduction in peak detuning of 42% [1].

## TUNING SENSITIVITY

Two other properties related to cavity detuning are measured during Acceptance testing. These are pressure sensitivity and the static Lorentz coefficient. As Tables 1 and 2 illustrate, these properties were also affected by the tuner modifications.

Table 1: Pressure Sensitivity (Hz / torr)

| | **C100-1** | **C100-2** | **C100-3** | **C100-4** | **C100-5** |
|---|---|---|---|---|---|
| **1** | 435 | 404 | 420 | **250** | **254** |
| **2** | 322 | 323 | 352 | **226** | **234** |
| **3** | 300 | 357 | 323 | **215** | **203** |
| **4** | 252 | 321 | 355 | **200** | **188** |
| **5** | 273 | 356 | 323 | **205** | **183** |
| **6** | 314 | 338 | 325 | **230** | **203** |
| **7** | | 379 | 355 | **213** | **214** |
| **8** | | 399 | 426 | **243** | **243** |

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Table 2: Static Lorentz Hz/(MV/m)$^2$

| | C100-1 | C100-2 | C100-3 | C100-4 | C100-5 |
|---|---|---|---|---|---|
| **1** | -2.35 | -2.23 | -2.27 | **-1.59** | **-1.60** |
| **2** | | | -2.18 | **-1.58** | **-1.68** |
| **3** | -1.98 | -2.08 | -2.04 | **-1.62** | **-1.43** |
| **4** | -1.95 | -2.08 | -2.14 | **-1.63** | **-1.58** |
| **5** | -2.05 | -2.11 | -2.01 | **-1.46** | **-1.55** |
| **6** | | -2.19 | -2.16 | **-1.54** | |
| **7** | -1.94 | -2.32 | -2.18 | **-1.61** | |
| **8** | -2.48 | -2.36 | -2.30 | **-1.47** | |

These two tables show that the tuner modification has led to a 37% reduction in pressure sensitivity and a 28% reduction in the static Lorentz detuning coefficient.

## GRADIENT PERFORMANCE

The C100 cavities are required to have an average maximum usable gradient equal to or greater than 19.2 MV/m in order to meet the design goal of 108 MeV per cryomodule. The maximum gradient of each cavity is determined first in the CMTF and again after the cryomodules are installed in the linacs.

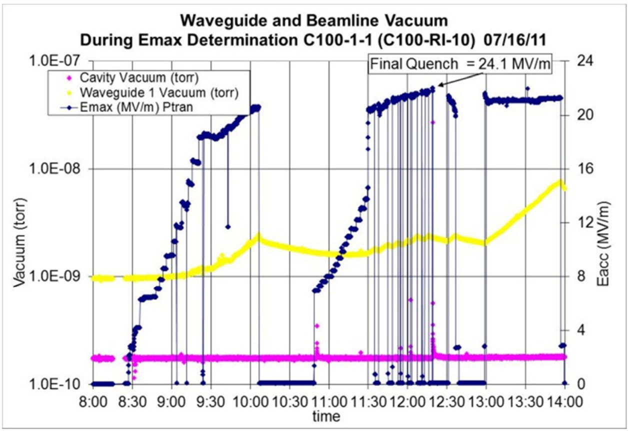

Figure 1: Maximum Gradient Determination

Figure 1 illustrates the process of raising a cavity to its maximum gradient (Emax) for the first time in a cryomodule along with the effects on both beam line and waveguide guard vacuums. This process can take as long as eight hours. Note that this cavity experienced multiple non-repeating quenches as the gradient was raised to its final maximum gradient at 24.1MV/m. This is typical behaviour for a cavity during this procedure.

In theory, there are a number of conditions that may limit the maximum gradient. These include, arcing in the waveguide vacuum space, vacuum degradation, rf window temperature, quenching, high dynamic (rf) heat load and an administrative limit of 25 MV/m. In practice, the cavities are limited by quenching, high rf heat load or the administrative limit. For single cavity operation, a dynamic heat load in the range of about 50–60 W would be considered to be too high for stable operation. Heat loads in this range will most likely cause "boiling" in the helium bath. This behavior manifests as large swings in the helium bath level and an increase in the helium bath pressure.

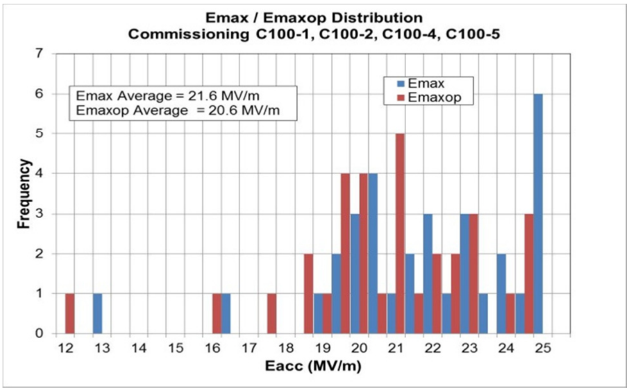

Figure 2: Emax / Emaxop Distribution.

Once the maximum gradient is known a determination must be made of the maximum stable operating gradient (Emaxop). This is done by lowering the gradient below Emax by an amount generally between 0.5 MV/m and 1.0 MV/m. The cavity is then operated at this new gradient for at least one hour. If no faults or cryogenic instabilities (such as boiling) occur, this gradient is designated as Emaxop for single cavity operation.

Figure 2 shows the distribution of maximum gradients for the first four installed C100 cryomodules. Note that there are three outliers in this distribution. The lowest gradient at 12.5 MV/m was the result of the beamline being vented to air during assembly, the next lowest suffered a quench induced field emitter during vertical test and was not reprocessed as would normally be done. The last of the three had a misadjusted stub tuner which led to waveguide vacuum problems. The stub tuner problem was later corrected after commissioning had been completed.

### *Field Emission*

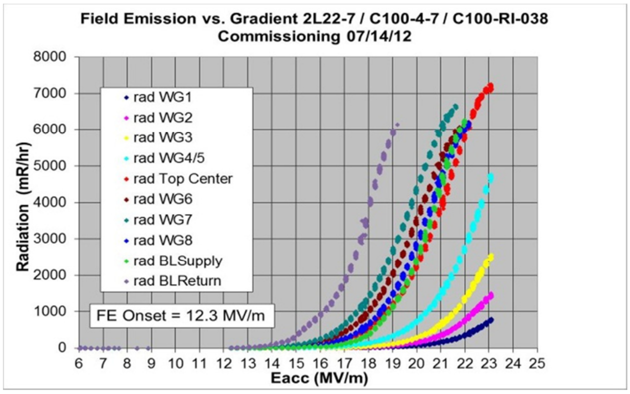

Figure 3: Typical Plot of X-Ray Production by Field Emission

After the Emaxop determination is completed, a measurement of x-rays produced by field emission as a function of gradient is made. A set of 10 Geiger –Mueller (GM) tubes are placed on the cryomodule at several locations including the beamline at either end of the cryomodule and at the Fundamental Power Couplers

(FPC's). Figure 3 shows the results for a typical cavity. Note that the GM tubes used saturate at approximately 7 R/hr. Figure 4 shows the distribution of field emission induced x-ray onset gradients for the four installed cryomodules.

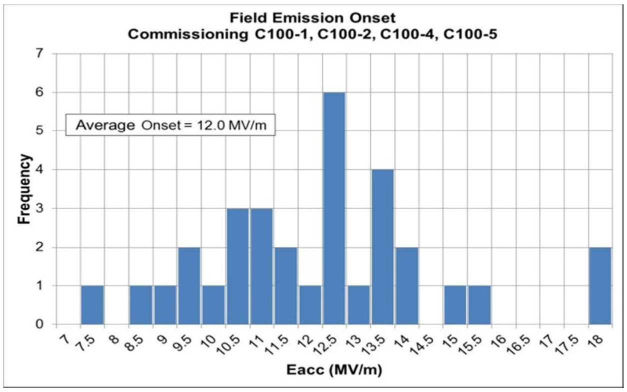

Figure 4: Field Emission Induced Onset of X-rays

## $Q_0$ AND HEAT LOAD

After the operating gradients have been determined, $Q_0$ vs. $E_{acc}$ is measured for each cavity. $Q_0$'s are measured calorimetrically. The cryomodule is isolated by closing the JT and RT valves and the rate of rise of the helium bath pressure is used to determine the rf heat load [2]. Figure 5 shows a typical $Q_0$ vs. $E_{acc}$ curve. Figure 6 shows the values of Q0 at Emaxop and at 2.07 K for the four installed cryomodules.

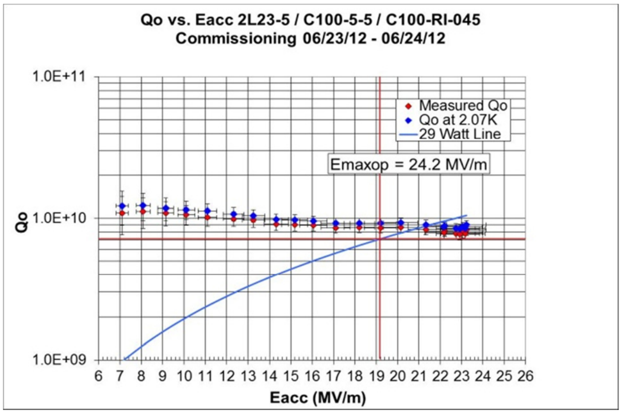

Figure 5: Typical $Q_0$ Plot

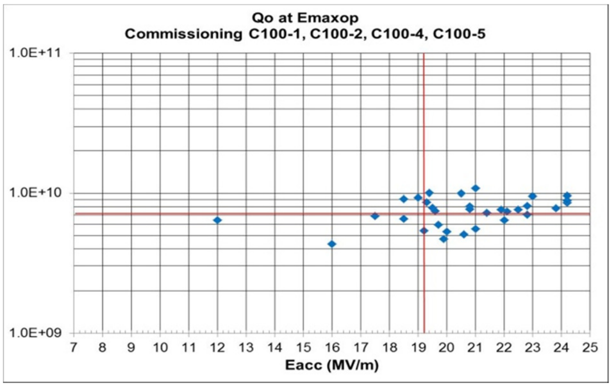

Figure 6: $Q_0$ at Emaxop

The $Q_0$ measurements are used to calculate a set of gradients at which the rf heat load equals 29 W but does not exceed Emaxop for a particular cavity. The 29 W value is based on a dynamic heat load budget for each cryomodule of 250 W that includes waveguide losses. If this budget is exceeded, boiling in the helium bath will begin and stable operations will not be possible. In cases where a cavity or cavities do not reach the 29 W heat load level due to other gradient restrictions, the gradients of other cavities in that cryomodule may be adjusted upwards. The final commissioning step is to attempt to operate all eight cavities simultaneously at these gradients for at least one hour. The average of these "ensemble" maximum operating gradients is 19.5 MV/m.

Table 3: Cryomodule Energy Gain (MeV)

| | Acceptance | Commission | Ops |
|---|---|---|---|
| C100-1 | 111.7 | 104.3 | 94.5 |
| C100-2 | 117.5 | 109.6 | 108 |
| C100-3 | 118.7 | | |
| C100-4 | 115.1 | 105.8 | 106.2 |
| C100-5 | 108.2 | 109.9 | 109.3 |

Table 3 lists energy gain for the first five cryomodules. It should be noted that the Acceptance test numbers are only predictions as the CMTF set up only allows for single cavity operation. Furthermore, only the first two cryomodules have been operated with beam. C100-1 has not yet been pushed to its maximum gradients with beam as efforts during the last physics run were focused on bringing C100-2 up to its maximum gradients with beam. On May 18, 2012, C100-2 was operated at 108 MV for over an hour at 465 µA, the design current for CEBAF [3].

## SUMMARY

Five C100 cryomodules have been tested in the CMTF. Four of these have been installed in the CEBAF linacs, two of which have been operated with beam. In testing, all five have met or exceeded the specifications necessary for successful operation in the 12 GeV CEBAF accelerator. One of the five cryomodules has been shown to be operable at the design energy and beam loading.

## REFERENCES

[1] K. Davis *et al.*, "Vibration Response Testing of the CEBAF 12GeV Upgrade Cryomodules," LINAC 2012, (2012).

[2] M. Drury *et al.*, "Commissioning of the CEBAF Cryomodules," PAC 1993, (1993).

[3] C. Hovater *et al.*, "Commissioning and Operation of the CEBAF 100 MV Cryomodules," IPAC 2012 (2012).