CEBAF SRF PERFORMANCE DURING INITIAL 12 GeV COMMISSIONING*

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) energy upgrade from 6 GeV to 12 GeV includes the installation of eleven new 100 MV cryomodules (88 cavities). The superconducting RF cavities are designed to operate CW at an accelerating gradient of 19.3 MV/m with a Q_L of 3×10^7. Not all the cavities were operated at the minimum gradient of 19.3 MV/m with the beam. Though the initial 12 GeV milestones were achieved during the initial commissioning of CEBAF, there are still some issues to be addressed for long term reliable operation of these modules. This paper reports the operational experiences during the initial commissioning and the path forward to improve the performance of C100 (100 MV) modules.

INTRODUCTION

In March of 2014 eleven new eight cavity high gradient cryomodules were operated for the first time in the CEBAF accelerator. The cryomodule design is a culmination of the lessons learned from three preproduction high gradient cryomodules and the original 42 CEBAF cryomodules [2]. To meet the 12 GeV energy goals the cryomodules must have an energy gain of 98 MeV. With that as a performance must, the cryomodule and cavities were designed to achieve 108 MV. Each cryomodule consists of eight 7-cell elliptical cavities. The cavities are tuned to 1.497 GHz, and individually controlled by both a mechanical stepper motor and a Piezo tuner (PZT).

Additionally the RF system is completely new for these cryomodules [3, 4]. Each cavity is powered and controlled by a single klystron and LLRF system. The klystrons produce 12 kW of linear power and up to 13 kW saturated. Four high voltage power supplies power two klystrons at a time. The eight klystrons are self-protected with their interlocks as part of the high power amplifier system. The RF controls use a traditional heterodyne scheme and digital down conversion at an intermediate frequency. Each cavity field and resonance control PI algorithm is contained in two FPGAs. One FPGA is in the field control chassis, controlling a single cavity. The resonance control chassis contains the other and controls up to eight cavities. The RF controls are unique incorporating a digital self excited loop (SEL) to quickly recover cavities. Controls and interfaces for both the HPA and the LLRF are provided through EPICS.

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RF SYSTEM/CRYOMODULE COMMISSIONING

RF System Commissioning

The RF systems and cryomodules were installed and commissioned between 2011 and 2013, while the CEBAF accelerator was off for the energy upgrade. Typically they are commissioned in series, first with the RF systems and then followed by cryomodule commissioning.

The RF power systems (circulators and waveguide directional couplers) were commissioned by powering the klystrons up to their saturated power level of 13 kW. The LLRF system (field control chassis (FCC), stepper motor chassis, cavity interlocks, Piezo amplifier and heater controls) was simultaneously tested and calibrated [3]. The new digital RF control has made testing much simpler and easier since it replaces the RF sources and analog phase lock loops used in the past.

Table 1: C100 Cryomodule Energy Gain

Cryomodule	Beam Measurement	During CEBAF Commissioning
C100-1	104 MV	94.01 MV
C100-2	122	93.8
C100-3	108	76.58
C100-4	93	79.24
C100-5	121	100.31
C100-6	111	101.8
C100-7	104	103.81
C100-8	110	100.17
C100-9	105	101.15
C100-10	106	87.57
C100-0	104	89

Cryomodule Commissioning

All cavity/cryomodule performance aspects were tested in the CEBAF tunnel as part of commissioning [5]. Typical measured values include Qo, Qext and max

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gradient. In addition to the maximum operable gradient, the limiting factor (Quench, heat load or administrative limit) is also determined for each cavity. Finally, all eight cavities are run together to ensure they can operate at their maximum operable gradients without interfering with adjacent cavities in the cryomodule. Table 1 shows the installed energy gain of each cryomodule [6].

Once the cryomodule commissioning is complete, the RF control system PI gain settings are optimized and the cavity gradient calibrations are uploaded with calibration values in to the EPICS control system.

BEAM OPERATIONS AND COMMISSIONING

Initially two C100 cryomodules were installed in the summer of 2011 and operated from October 2011 to May of 2012 [6, 7]. A goal for this beam operation period was the demonstration that the new cryomodules could achieve an energy gain of 108 MeV at the CEBAF design linac current of 465 µA. To achieve this, the eight cavities needed to maintain an average gradient of 19.3 MV/m. So that the demonstration would have program value, an additional constraint was placed that the cryomodule must maintain this energy for one hour with no faults. In May of 2012 the cryomodule achieved 108 MV for over an hour with a beam current of 465 µA.

An additional nine C100s were installed during the 16 month accelerator down between 2012 and 2013.

For the first time, ten C100 cryomodules were operated continuously from January 2014 through May 2014 (all eleven from March 2014), except for a month down between February and March of the same year. We were able to achieve the initial commissioning goals of energy of 2.2 GeV/pass which corresponds to 12 GeV in the machine and injector energy of 123 MeV. During this time they also supported the Lab's nuclear physics program. Cryomodule voltage ranged from 50 MV to over 100 MV depending on the requirements for the experiments.

Operation of these new cryomodules is different than the older 42 installed in CEBAF. The cavities have four times higher Q_{ext} (3×10^7 vs. 6.6×10^6) and a Lorentz coefficient of approximately -2 Hz/(MV/m)^2. With the narrower cavity bandwidths and higher gradients, automated turn on and recovery applications are important to maximize machine up time.

Even though we were able to achieve the initial commissioning goals there is scope for improvement in some of the areas. Some of these things are reducing Field Emission, Microphonics detuning, Enhanced Cryomodule heater controls, RF control loop optimization and Crosstalk on Klystron drive cables. These issues are discussed in detail in the following sections.

Field Emission

Cavities in certain C100 modules were radiating high levels of field emission which was causing the beamline vacuum pumps to hit the fault limit. These are slow limits, which would charge the vacuum pumps to the limit every hour. Beamline vacuum pumps will turn RF off into all the cavities in the zone, thus making the recovery process longer. Operators noticed the pattern and through methodical investigation, cavities that were causing problems were detected and the gradients in those cavities were lowered. Cavities 6 and 7 and C100-10 were emitting high levels of radiation and were lowered to 10 MV/m (from 20 MV/m and 15.4 MV/m) to prevent the vacuum pumps from faulting (shown in figure 1).

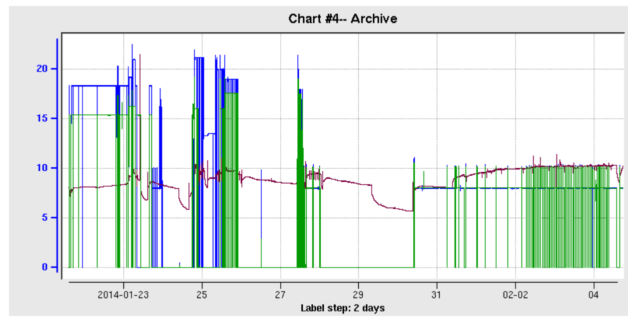

Figure 1: Showing Beamline Vacuum level in C100-10 cryomodule when gradients were lowered to 10 MV/m (Dark Red is the Beamline vacuum, Blue and Green are gradients in Cavity 6 and 7)

Helium Processing

Helium processing was proposed to minimize the field emission from cavities and to also to gain the lost gradient in the cavities over few years of operations. To understand the benefits of He processing, C100-3 cryomodules was processed in the winter of 2015. He processing dramatically improved the field emission performance of the cavities. As shown in Figure 2, He processing moved the field emission onset to a higher gradient and radiation is approximately a tenth of what it was before for the same gradient.

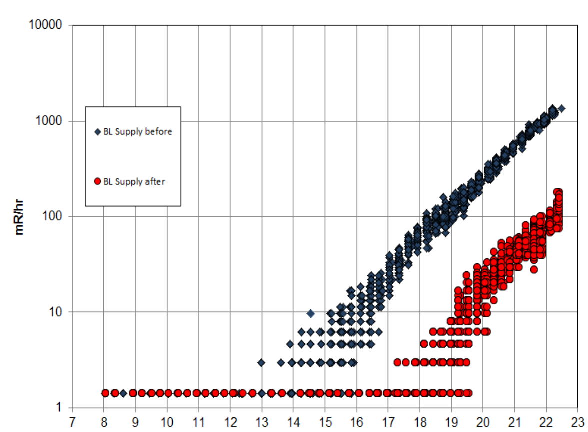

Figure 2: Field emission levels of C100-3 cavity 6 before and after He processing

It is planned to process all the modules with He in the summer. This will minimize the radiation and the cavities

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that are limited by field emission can be operated at their E_{max} values.

MICROPHONICS DETUNING

Mechanical Tuner Modification

Initial testing of the first cryomodule (C100-1) showed that it marginally met the design goals for microphonic detuning [6]. The peak detuning was specified as 25 Hz total peak detuning broken down into 18 Hz dynamic and 4 Hz static. Figure 3 shows the amount of detuning on cavity 4 when cavity 3 faults

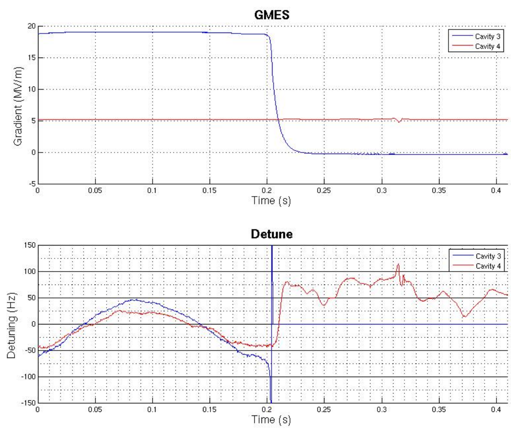

Figure 3: Graph of gradient and detuning (Hz) as a cavity is faulting (blue).

The results were a concern considering that in earlier prototype testing they were lower. It was determined that the cavity cell shape was at least partially responsible for the increased microphonic susceptibility.

The solution was to modify the tuner pivot plate. Figure 4 shows the tuner modification and the reduction of the microphonics with the modification.

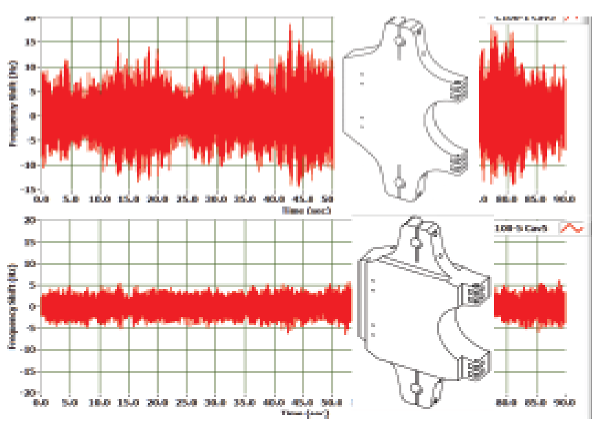

Figure 4: Time domain microphonics data before and after tuner modification

On average the cavity microphonic detuning was reduced by 42%. Table 3 shows the improvement in microphonics between C100-1 and C100-4. Fortunately the last seven cryomodules were able to receive the tuner modification

Microphonics Due to External Activity

During CEBAF commissioning there was construction activity going on near injector where C100-0 was installed. It was noticed that C100-0, C100-1 and C100-2 were much more susceptible to the external activity. As shown in figure 5, C100-0 was performing much better between 5 PM and 7 AM, when there was little outside activity.

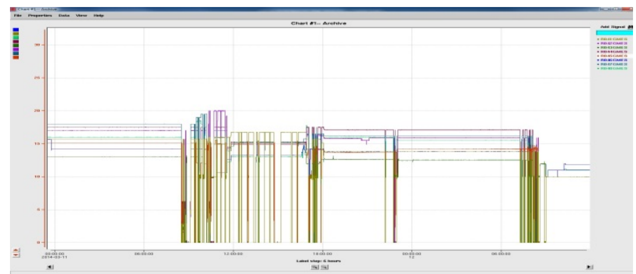

Figure 5: Gradient stability of cavities in C100-0 over 30 hours. Cavities are much quieter between 5PM and 7AM.

Until the on-site construction was completed, gradients in the C100-0 cavities were lowered to give headroom for the detuning caused by external perturbation. Also the Klystrons in injector are only 8 kW as opposed to 13 kW in the linacs. These cavities have lower power margin for microphonics detuning when compared the ones in the linac. The reason for 8 kW Klystrons in the injector is the beam current. Beam current in the injector won't be more than 200 uA as opposed to 465 uA in the linac. It is planned to collect the data from all the C100s and do the analysis on microphonics. Once the analysis is done, the C100 least susceptible to microphonics will be moved to injector to minimize the downtime. In addition other options are being investigated to improve the performance such as more sophisticated PZT algorithm to compensate for microphonics.

CRYOMODULE HEATER CONTROLS

Each cryomodule has eight resistive heaters (one for each cavity) to balance the heat load between when RF is on and when it is off. This is essential for seamless cryogenic plant operations. In the original cryomodules, there was no need for individual cryomodule heater controls (referred to as C20 & C50) as the helium vessels were large enough to conduct the heat. Typically He liquid level is fairly constant in a cryomodules. It isn't the case with C100 modules. Whenever there is a mismatch between RF and Electric heat, He liquid level begins to bounce. The cause is believed to be due to the He riser in each cavity's cryostat, a potential choke point.

Single Heater Control

When one heater stops working or causes microphonics in the cavity above a certain amount of electric heat, it is difficult to lower the heat applied to that specific cavity. In C100-1, there was a problem with one of the heaters and whenever the total Electric heat in the module was above 130 watts (16 watt/cavity), it was inducing microphonics in the cavities. As soon as the electric heat was below 130 watts cavities were stable. After investigation it was found out the heater for Cavity 6 was causing the detuning (shown in figure 6). Due to this total electric heat in the module had to be lowered. But this cryomodules was operating at a total gradient where the RF heat load was approximately 210 watts. In the event of a whole zone fault, it will cause mismatch between RF heat and electric heat.

Network Delay on Heater Control

Heater control ioc receives the gradient information through EPICS over the network. When there is a change in the gradient, it takes about five seconds (defined from the EPICS scan rate for this application) for the information to be in sync.

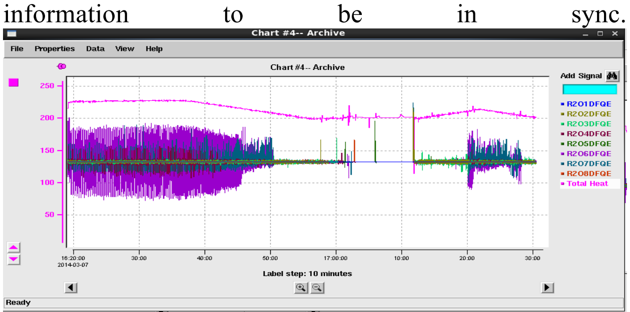

Figure 6: Effect of electric heat on cavities in C100-1. Cavities 6 and 7 have very high detuning (in SEL)

The extreme cases for this configuration are when the whole zone faults and zone is turned on. In both cases there is a large heat mismatch for five seconds. In some instances the zone had to be turned off for a while for the liquid level to be stable (shown in figure 7). Heat mismatch issues were noticed in all the new zones, but they were more predominant in some zones than the others.

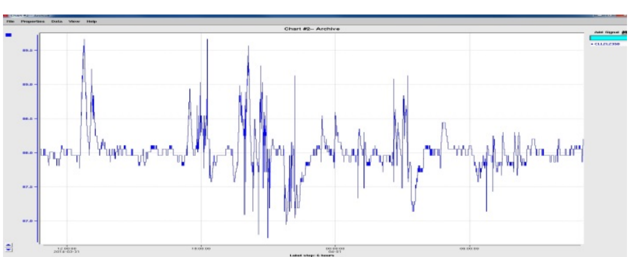

Figure 7: Effect of heat mismatch on liquid level in C100-5, after a zone fault. RF was turned off for 30 minutes for the liquid level to be stable.

New control system in design will receive gradient information in that zone over 5 MHz fiber, thus reducing the delay and the transition between electric and RF heat will be faster than the cryogenic system can react. We are planning to install the new system in all of the zones over the next year.

RF CONTROL LOOP OPTIMIZATION

When cavities were operating in GDR, we noticed 4.1 kHz oscillation on the Probe signal on random cavities. Increasing the proportional gain lowered the oscillation. At higher gains control system was less stable. On further review we noticed that the loop phase was not optimized for GDR and by optimizing the phase, oscillations went away and thus gains could be increased.

CROSSTALK ON KLYSTRON DRIVE CABLES

C100 cavities are operated using one control system and one klystron. During the initial commissioning we noticed crosstalk on some of the RF drive cables and cavities were faulting on GMES fault (Gradient measured when there is no RF). We noticed few cables that were not properly terminated and those were fixed. Even after all the faulty cables were fixed there were still issues with RF leakage. To better understand this, one of the klystron inputs was terminated with a 50 ohm load at its input. In this case control system was reading about 20 watts of RF power and the cavity was producing about 0.7 MV/m. It was more likely the RF cables inside the solenoid were causing these problems. Also the 13 kW Klystrons have high gain (50 – 65 dB). The next step in investigating this is to replace the cable inside the solenoid with a better shielded one and repeat the measurements to detect the source of crosstalk.

SUMMARY

The eleven CEBAF 100 MV cryomodules have been successfully operated for nuclear physics experiments. Most of the 12 GeV milestones were achieved i.e 2.2 GeV/pass with beam, injector energy of 123 MeV, greater than 10.1 GeV beam (5.5 pass) to Hall D and 3 pass and greater than 6 GeV beam to Hall A.

CEBAF commissioning is underway and on the way to 12 GeV era of nuclear physics experiments. To deliver the physics quality beam to the experimental halls with minimum down time, all the above discussed issues need to be fixed for reliable operation. Things like He processing will help in gaining the lost gradient over the years of operation and minimizing the field emission. If C100 modules can reliably operate with a minimum gradient of 100 MV, there will be headroom for RF gradient to minimize the downtime associated with it.

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