OPERATIONAL EXPERIENCE WITH CW HIGH GRADIENT AND HIGH Q_L CRYOMODULES*

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) energy upgrade from 6 GeV to 12 GeV includes the installation of ten new 100 MV cryomodules (80 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. The RF system employs single cavity control using new digital LLRF controls and 13 kW klystrons. Recently, all of the new cryomodules and associated RF hardware and software have been commissioned and operated in the CEBAF accelerator. Electrons at linac currents up to 10 μA have been successfully accelerated and used for nuclear physics experiments. This paper reports on the commissioning and operation of the cryomodules and RF system.

INTRODUCTION

In January of 2014 ten new eight cavity high gradient cryomodules (designated as C100) 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 [1]. 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 [2, 3]. 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.

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.

Cryomodule Commissioning

All cavity/cryomodule performance aspects were tested in the CEBAF tunnel as part of commissioning [4]. Typical measured values include Qo, Qext and max 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. Figure 1 compares the installed maximum gradients of the new cavities to the vertical test data [4]. Table 1 shows the installed energy gain of each cryomodule [5].

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

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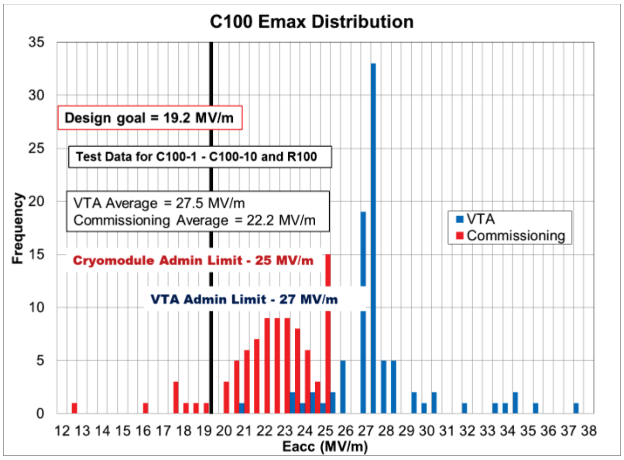

Figure 1: Emax distribution between the installed cavities and data taken during cavity vertical test.

Table 1: C100 Cryomodule Energy Gain.

Cryomodule	RF Measurement	Beam Measurement
C100-1	110 MV	104 MV
C100-2	120	122
C100-3	124	108
C100-4	105	93
C100-5	110	121
C100-6	113	111
C100-7	113	103
C100-8	109	110
C100-9	117	105
C100-10	116	106

OPERATION AND CONTROL

Initially two C100 cryomodules were installed in the summer of 2011 and operated from October 2011 to May of 2012 [6]. 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 eight 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, except for a month down between February and March of this year. During this time they 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.

Cavity Field Control

The stability of the amplitude and phase of the cavity fields plays an important role in the beam energy spread, a critical figure of merit for nuclear physics experiments. Table 2 shows cavity field maximum allowable errors and the average measured rms. values for the C100 cryomodules needed to preserve beam energy spread of 10^{-4} (FWHM) [7]. Meeting this requirement can be difficult when considering the cavity microphonics background of 4 Hz rms. and a peak detuning (6σ) of 24Hz. In our case the new digital LLRF system met this requirement with some margin. In fact the phase error would be much better, but it is dominated by the phase noise of the local oscillator.

Table 2: Cavity field stability requirements and average measured values.

	Requirement	Measured
Amplitude RMS error	4.5×10^{-4}	2.8×10^{-4}
Phase RMS error	0.5°	0.08°

Cavity Turn On

To compensate for the Lorentz effect, the cavity turn on sequence utilizes both firmware and EPICS application software. With a Lorentz coefficient of 2 and at the intended gradient of 20 MV/m, detuning is 800 Hz from RF off to RF on. Other accelerators have used a Piezo tuner to compensate for the Lorentz effect at turn on by using a feed-forward algorithm. At JLab we have gone in a different direction and employ a digital self-excited loop (SEL) that tracks the cavity frequency and quickly restores the cavity to its operational gradient. A firmware application then tunes the cavity and switches to Generator Driven Resonator (GDR) mode, locking the cavity to the reference. Figure 2 shows a plot of the forward power/phase and I/Q signals as it is switched from SEL to GDR.

The procedure has evolved to the point that it is a "single button" automated turn on for the high gradient cryomodules. Each cavity is turned on in the SEL mode at

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some nominal gradient (18 MV/m for example) and then tuned to the reference frequency. Once on resonance the automated algorithm locks the cavity to the reference and then adjusts the gradient for the accelerator needs.

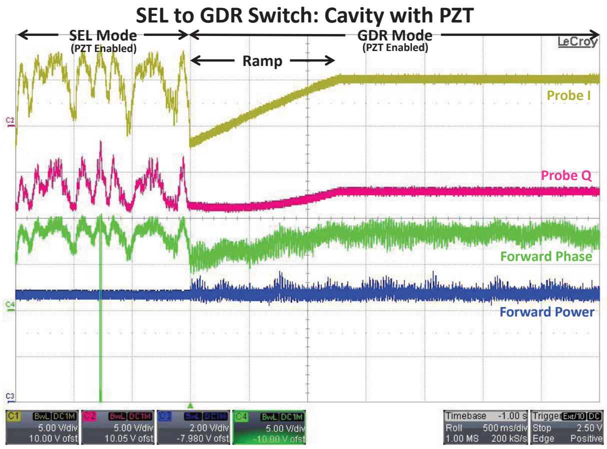

Figure 2: Transition from SEL to GDR.

Cavity to Cavity Coupling

The mechanical coupling between adjacent cavities is roughly 10% in C100-1 through C100-3. This can present a problem when a cavity turns off suddenly (fault). If cavity one detunes 800 Hz due to the Lorentz effect when faulted, cavity two will see 80 Hz of detuning. When you factor in the Q_{ext} is $3x10^7$ for the cavities, this implies a bandwidth 50 Hz. The Lorentz push from an adjacent cavity turning off is more than a bandwidth and the klystron does not have the overhead at higher gradients to compensate for such a detuning. To demonstrate this, a Piezo tuner (cavity 5) was stepped abruptly 460 Hz off resonance (Figure3). The closest adjacent cavity, which is six, saw detuning of approximately 50 Hz. Other cavities 4, 7 and 8 saw a smaller detuning. It should be noted that between cavity four and five there is a support making the coupling less. The "ringing" is the cavity mechanical mode of 21 Hz.

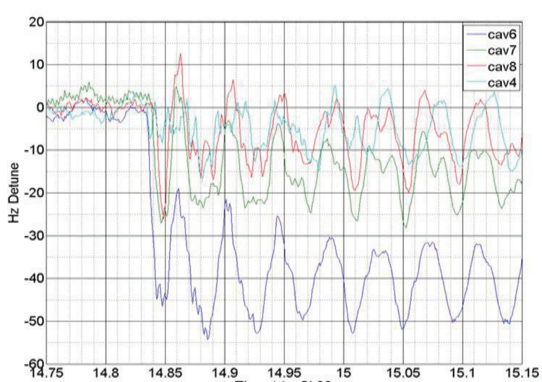

Figure 3: Shows the Piezo step response of cavity 5 on adjacent cavities (4, 6, 7, and 8).

When a cavity faults, the adjacent cavities are immediately switched to SEL, to keep them at gradient and prevent the fault from cascading though the entire module. The tuners are also disabled to preserve the general tuner setup of the module. Once the faulted cavity is cleared and brought to gradient, all the cavities are tuned and switched back to GDR using the automated EPICS and firmware application.

Cavity Microphonics

Cavity microphonics are measured continuously by determining the detuning angle from the cavity signal and the forward power. In EPICS it is displayed in both a peak and rms. number for each cavity. Figure 4 shows the detuning in Hz for rms. and peak for a typical cavity.

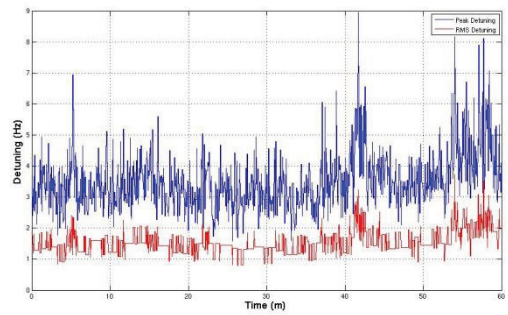

Figure 4: Rms. average and peak microphonic detuning of a cavity.

LLRF Data Buffers

A useful feature possible on digital LLRF control systems is the use of data buffers. The hardware allows the operator to capture real time data from the cavity-control system. This is extremely useful when diagnosing cavity faults or measuring microphonics. Figure 5 is a plot of a cavity fault. The top graph displays the cavity gradient of the faulted cavity and the adjacent cavity. The bottom graph shows each cavity's detuning in Hz. The red curve on the bottom graph shows the sharp reaction of the non-faulted cavity to the Lorentz contraction from the faulted cavity. The adjacent cavity was operating at a fairly low gradient, 5 MV/m, so the klystron had more than enough overhead to absorb the 77 Hz detuning.

Mechanical Tuner Modification

Initial testing of the first cryomodule (C100-1) showed that it marginally met the design goals for microphonic detuning [5]. The peak detuning was specified as 25 Hz total peak detuning broken down into 21 Hz dynamic and 4 Hz static.

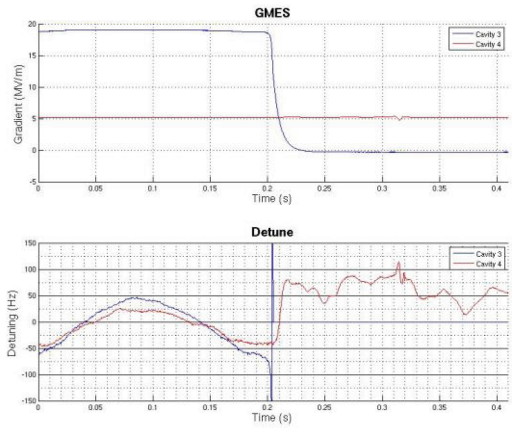

Figure 5: Graph of gradient and detuning (Hz) as a cavity is faulting (blue).

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 6 shows the tuner modification and the reduction of the microphonics with the modification.

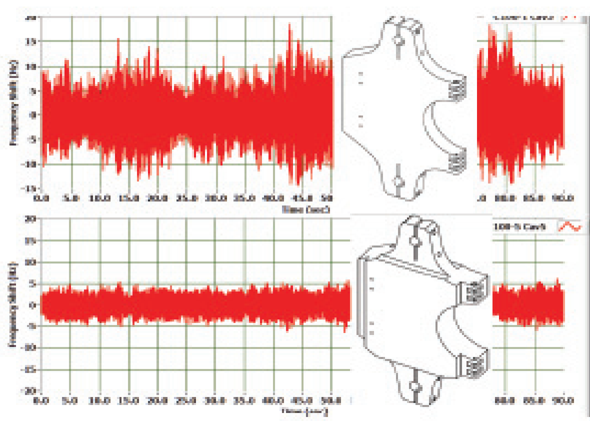

Figure 6: Time domain microphonics data before and after tuner modification.

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 before assembly. The first three were already assembled by the time the fix was determined.

Table 3: Cryomodule microphonic detuning comparing the non-modified to modified cryomodules.

Microphonic Detuning	C100-1	C100-4
RMS (Hz)	2.985	1.524
6σ (Hz)	17.91	9.14

Cryomodule Resonance Control

Cavity frequency control is provided by a mechanical stepper motor and a PZT. The stepper motor provides coarse tuning and can tune the cavity to ± 1 Hz of the reference. The drawback is that it is slow ≤ 0.1 Hz, and can disturb adjacent cavities.

The PZT provides "close in" fine tuning control (± 1000 Hz). The control bandwidth (speed) is 1 Hz and is limited by the mechanical resonances of the cavity. Even with this relatively slow control, the effect is dramatic on cavity tuning. Figure 7 shows the cavity detuning with and without the PZT turned on while locked in GDR mode. Presently the PZT control algorithm is a simple PI feedback.

Moving the PZT control bandwidth beyond a few Hz resulted in the loop oscillating and increasing the background microphonics. The oscillations were at the cavity mechanical frequency of 11 Hz. The reason for the oscillation is not fully understood and we plan to make additional PZT tests in the future.

Initially the PZT voltage was centered at 75 volts, for a full range of 150 volts. During testing of the first two C100 cryomodules a number of Piezo failures were observed. An investigation showed that the electrical leads on the Piezo stacks were possibly breaking down.

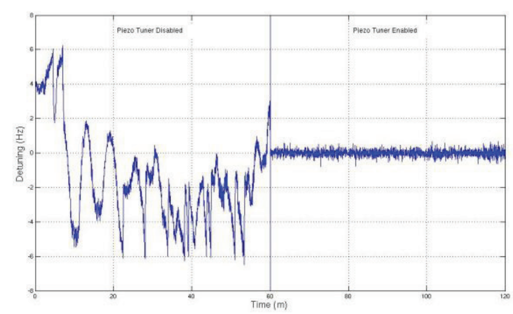

Figure 7: PZT off vs. on.

In consultation with the vendor to determine the optimum tuning range needed to control He detuning, the peak voltage was lowered to 50 volts.

Another modification made to the resonance control was to speed up the mechanical tuner stepper response. Only the first three cryomodules have Piezo tuners installed (a cost decision). The last seven do not need Piezo tuners because of the reduced detuning and pressure sensitivity. Only the mechanical tuner is needed to keep the cavities tuned. Initially the mechanical tuners were driven with tuning information supplied across the EPICS network. Because of EPICS limitations the cavity tuners were not updated quickly enough. To fix this a direct fiber connection was used between the field control chassis and the stepper motor driver chassis. This eliminated the lag between the command and actual tuning, allowing for tighter and faster tuner control.

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Cryomodule Heaters

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. Originally the heater control was one power supply controlling four of the resistive heaters (cavities 2, 4, 6 and 8). As we began operations last winter, at times we noticed that if we lost a cavity (1, 3, 5 or 7), we would observe increased cavity microphonics in the cryomodule. Figure 8 shows He liquid level reacting to cavity resistive heat. Typically He liquid level is fairly constant in a cryomodule. In this case it began to bounce because of He boiling from the added resistive heat. The cause is believed to be due to the He riser in each cavity's cryostat, a potential choke point.

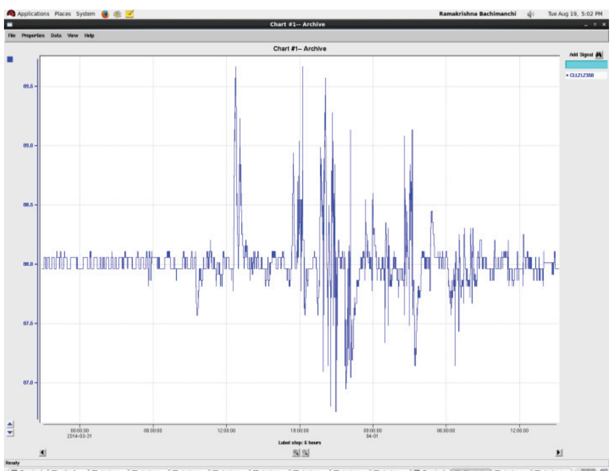

Figure 8: Showing He liquid level in a cryomodule when the resistive heaters are turned on.

If a cavity was turned off; the resistive heat in the even cavities would be raised to keep the heat load constant in the cryomodule. In some cases this increased the heat in the even cavities beyond what the He riser was designed to handle, causing He boiling. This in turn would cause violent microphonic activity essentially detuning the cavities beyond what the RF power and controls could effectively compensate.

The obvious solution is to operate the heaters individually so that the heat in cavity-cryostat remains below the heat the riser is designed to accommodate. In our case we quickly engaged the other four resistors so that all eight are powered but still controlled as one. This helped minimize the problem by distributing the heat, but it is not a complete solution. We plan to implement individual heater control next year.

SUMMARY

The ten CEBAF 100 MV cryomodules have been successfully operated for nuclear physics experiments. Cryomodule energies up to 108 MeV and cavity gradients over 20 MV/m have been run CW for hours with little down time associated with them. Operational issues have been overcome by hardware modifications and implementing fixes in both local firmware and EPICS software. Cavity faults have been mostly from external influences and not intrinsic to the cavity or coupler design making them easier to mitigate. In the future, work is planned to reduce cavity recovery time and to further understand the Piezo tuner to cavity dynamics.

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