CEBAF UPGRADE: CRYOMODULE PERFORMANCE AND LESSONS LEARNED*

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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 the Continuous Electron Beam Accelerator Facility (CEBAF) from 6 GeV to 12 GeV. The increase in beam energy will largely be due to the addition of ten C100 cryomodules and the associated RF in the CEBAF linacs. These cryomodules are designed to deliver 100 MeV per cryomodule. Each C100 cryomodule contains a string of eight seven-cell, electro-polished, superconducting RF (SRF) cavities. While an average performance of 100 MV is needed to achieve the overall 12 GeV beam energy goal, the actual performance goal for the cryomodules is an average energy gain of 108 MV to provide operational headroom. All ten of the C100 cryomodules are installed in the linac tunnels and nine have been commissioned as of September 2013. Commissioned performance has ranged from 104 MV to 118 MV. In May, 2012, a test of an early C100 achieved 108 MV with full beam loading. This paper will discuss the performance of the C100 cryomodules along with operational challenges and lessons learned for future designs.

INTRODUCTION

The 12 GeV upgrade to the CEBAF accelerator, currently operating at 6 GeV, is a large scale project that requires the installation of several key components to allow for the machine to operate at the increased energy [1]. These components include added acceleration, an additional recirculation arc, stronger magnets, new beam line, a new experimental hall, Hall D and the doubling of the cryogenic capacity of the central helium liquefier (CHL). The added acceleration comes in the form of 10 new cryomodules and the associated RF infrastructure. The new cryomodules are installed at the ends of the existing linacs, five in each linac.

The C100 cryomodule was designed to provide, on average, 108 MV from a string of eight 7-cell low-loss shaped SRF cavities within a heat budget of 300 Watts for the primary 2K helium circuit [2].

All ten of the C100 cryomodules have been assembled and have undergone successful Acceptance tests in the Cryomodule Test Facility (CMTF). After installation in the linacs and cool down to 2K, all but one of the cryomodules (C100-8) have been commissioned. Commissioning tests, so far, have demonstrated that these cryomodules are capable of delivering an average 110 MV per cryomodule.

The first two of the installed cryomodules have been operated with beam over a six month period during CEBAF's final 6 GeV experimental run which ended in May 2012.

C100 CRYOMODULE

The Cavity

A C100 cavity is shown in Figure 1.

Figure 1: C100 Cavity.

The C100 cavities undergo a processing regime that includes buffered chemical processing, electropolishing, heat treating, and multiple high pressure rinses.

The first key items that make this processing cycle unique, as well as very efficient, is the use of a bulk, 150 µm, buffered chemical polishing (BCP) of the interior of the cavity combined with a light, 30 µm, electropolishing (EP), prior to vertical RF testing in the vertical testing area or VTA [3]. The EP process helps provide a more uniform, smoother RF surface while also reducing the amount of Q slope exhibited during cavity testing [4].

The heat treating consists of a10 hour, 600 C bake and is designed to remove hydrogen gas from the cavity structure. After individual helium vessels are installed on each cavity, the cavities undergo a low temperature bake at 120 C for 24 hours prior to VTA testing. Several iterations of high pressure rinsing are applied during final assembly and after qualification in the VTA.

Qualification of the cavity in the VTA includes a determination of maximum gradient, Q_0 vs. Eacc and field emission measurements. Cavities also undergo a higher order mode (HOM) survey. The C100 cavities are expected to reach an average gradient of 19.2 MV/m with a Q_0 of 7.2E9.

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Overall there were 3 cavities that were not qualified to be installed into a cryomodule, one due to a defect on an equator weld, (cat eye defect), one that did not meet the HOM specification and one that was too far outside of our field flatness specification to be used. Otherwise, 96% of the cavities met the requirements for use in a C100 cryomodule, a testament to the quality of the design and fabrication, the robustness of the processing cycle as well as the skill of the technicians who carried out the work [5].

A cavity was considered to require reprocessing if it did not meet the Q vs E specification described above, or if it was producing more than ~ 10 mSv/hr of radiation at 19.2 MV/m. Figure 2 depicts the amount of reprocessing that was required to qualify a C100 cavity.

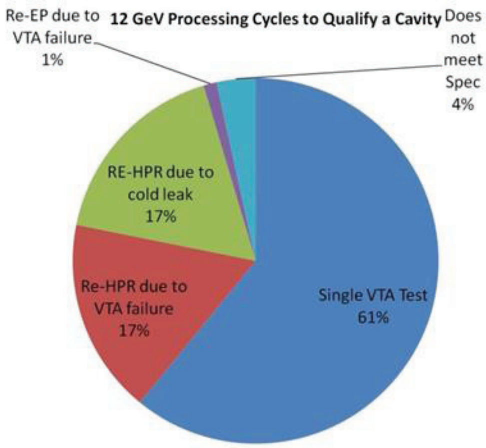

Figure 2: Cavity Reprocessing Cycles.

This paper will examine some of the results of VTA testing in relation to similar tests made of cavities installed in the cryomodules.

The Cryomodule

After VTA qualification, cavities undergo a final high pressure rinse and are staged in a Class 10 clean room for assembly into a string. Figure 3 shows a C100 string assembly in progress.

Figure 3: Cavity String Assembly.

After the string assembly is completed, the string is delivered to the Cryomodule Assembly Area.

A cavity string that is installed in a cryomodule is magnetically shielded by an inner cold layer of Cryoperm® and a concentric, warm outer layer of mu-metal. Figure 4 shows a C100 cryomodule during installation in the linac tunnel.

Figure 4: C100 cryomodule in the Tunnel.

The thermal design of the cryomodule consists of two cooling circuits, a 2 K primary circuit and a 50 K shield circuit via the two L shaped cryogenic end-cans and is thermally insulated with Multi-Layer Insulation (MLI) and an insulating vacuum space [6].

RF power is supplied through a waveguide power coupler assembly. The cavity vacuum is protected by a guard vacuum space between two warm ceramic RF windows.

The cryomodule was designed so that it would have no helium to cavity vacuum joints. This was done to avoid the risk of superfluid leaks into the cavity vacuum space.

The cavity tuning system consists of a cold scissor-jack mechanism driven by a warm stepper motor that keeps each cavity correctly tuned on frequency. The tuner assembly includes the provision for a piezo electric drive if needed for fine or fast control.

The eight-cavity string is supported and aligned by nitronic rod supports and a space frame assembly that is inserted into the vacuum tank.

CRYOMODULE TESTING

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

Acceptance testing takes place in the CMTF and is 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 feed-thru during cool down that leads to the loss of insulating vacuum. Such problems are more easily addressed while the cryomodule is in the CMTF which is adjacent to the Cryomodule Assembly Area.

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Once the cryomodule has been installed in a linac, it is commissioned. Commissioning consists of a subset of the Acceptance tests and is focused on determining stable operating gradients, measuring field emission, Q_0 and microphonics. Commissioning also offers an opportunity to operate all eight cavities at the same time. During commissioning, the cavities are powered by individual 13 kW klystrons and are controlled with the new digital LLRF controls running in a "self-excited loop" mode (SEL). Control and data acquisition is enabled through a combination of Labview and epics software.

This paper will focus mainly on commissioning results and will offer some comparisons to the results of VTA testing.

CAVITY PERFORMANCE

Maximum Gradient Determination

The C100 cavities are required to have an average usable gradient of at least 19.2 MV/m in order to meet the design goal of 108 MeV per cryomodule. The maximum gradient (Emax) of each cavity in the cryomodule is determined first in the CMTF and again after installation in the linacs.

The process of determining Emax is fairly simple. RF power levels are first calibrated using known RF cable losses. The gradient is calculated using emitted power. This gradient measure is used as a reference in order to calibrate the gradient based on RF power as measured at the cavity field probe.

The gradient is then stepped up slowly and in small increments using pulsed RF. In most cases, the cavity will go through a series of quenches at increasing gradients until further increases are limited by RF faults or the administrative limit of 25 MV/m. The administrative limit is set by the expected availability of RF power. The limit is then tested with CW RF.

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 loads or the administrative limit [7]. Figure 5 shows the Emax distribution for the C100 cavities from both VTA and commissioning tests.

The average maximum gradient for cavities installed in cryomodules is 22.2 MV/m and is about 5 MV/m lower than the VTA average of 27.4 MV/m. Some of this reduction can be attributed to a lower administrative limit for commissioning.

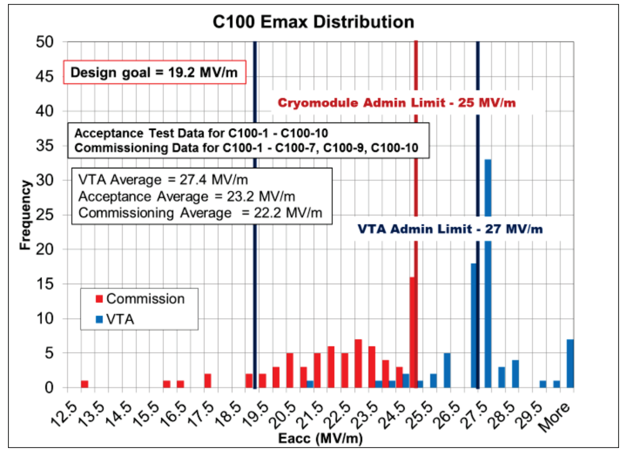

Figure 5: Emax Distribution for VTA and Commissioning .

Another cause of the reduction in gradient is the cryomodule itself. The cryomodule's primary circuit is designed to handle a heat load of up to 300 W. That heat budget includes the RF heat load of 29 W per cavity and also includes contributions from the power couplers and an average static heat load of 18.2 W. If that heat budget is exceeded, we begin to see instabilities in the liquid helium bath that manifest as rapid oscillations in the liquid level and increasing helium pressure. Alternatively, the riser pipes between the individual helium vessels and the two phase return pipe are only capable of passing 40-50 W before the helium temperature rises above lambda. In other words, the operation of an individual cavity can have the same destabilizing effect on the helium bath as the operation of the entire string at a heat load above 300 W.

In the nine cryomodules commissioned so far, about 21% of the cavities have gradient reductions that can be attributed to limitation by heat load. Another 15% of the cavities have gradient reductions that can be attributed to the more conservative administrative limit. If the administrative limit for VTA testing had been set at 25 MV/m, the VTA average would be 24.9 MV/m or less than 2 MV/m higher than the commissioning average. About 5% of the cavities have suffered performance reductions due to events such as vacuum contamination during the assembly process or the creation of a new field emitter after a quench while testing.

Most of the Emax determination process is performed with pulsed RF as a means to mitigate the risks of quenching the cavity at high gradient by lowering the average RF power.

After the maximum gradient has been determined, the cavity is operated for an extended period (at least one hour) to determine a maximum stable operating gradient, Emaxop. Emaxop will in most cases be lower than Emax. The average for Emaxop, for cavities commissioned so far, is 21.2 MV/m.

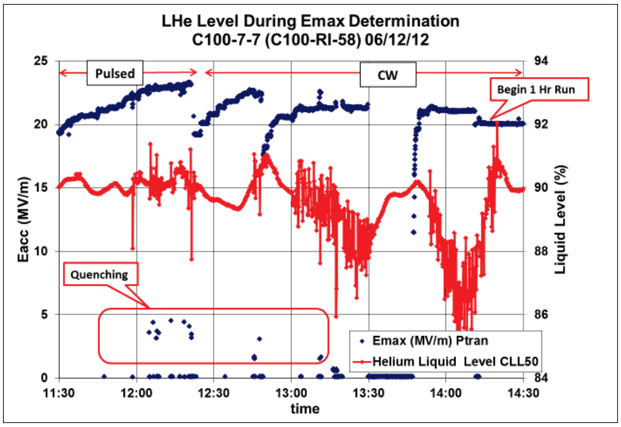

Figure 6: Emax Determination.

Figure 6 shows the gradient and helium liquid level during the Emax determination for cavity C100-7-7. This figure shows the cavity processing through a series of quenches at increasing gradients using pulsed RF until a hard quench limit is reached. It also shows the response of the helium bath to high RF heat load when the RF is switched to CW. At the far right side of this figure, after some lowering of gradient, the helium bath has stabilized and the one hour run can proceed.

Field Emission

After the Emaxop extended run 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 is 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 7 shows a set of measurements for a typical cavity.

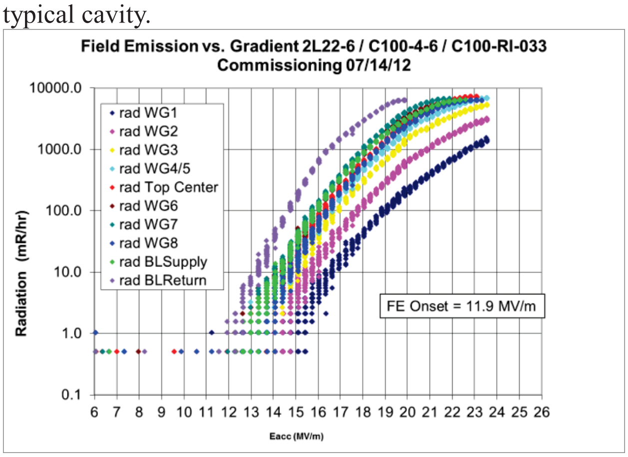

Figure 7: Plot of X- Ray Production for a Typical Cavity.

It should be noted that the GM tubes used for this measurement tend to saturate at approximately 7 R/hr. Figure 8 shows the distribution of maximum gradients that can be reached with no field emission. The average of these gradients for commissioning is 13.0 MV/m and for the VTA, 18.1 MV/m.

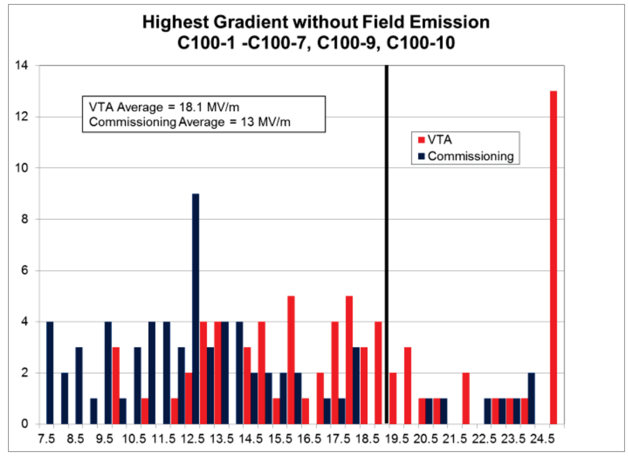

Figure 8: Distribution of Field Emission Onset.

Some of the difference might be attributable to differences inherent in measuring a cavity in a dewar as opposed to a cryomodule. Certainly that does not account for all of the change. In general, field emission onsets were lower for cavities in installed cryomodules than for cavities tested in the VTA.

Neutron production was also measured on the first two cryomodules that were installed. This, however, has not been a routine measurement on the full C100 set.

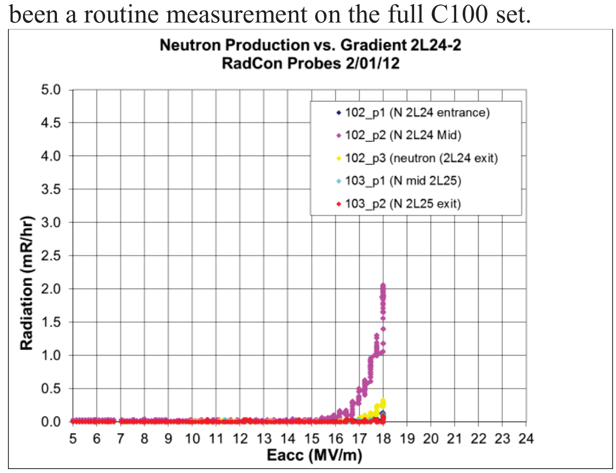

Figure 9: Neutron Production vs. Gradient.

Figure 9 shows neutron production vs. gradient as measured for a cavity in the second C100 cryomodule.

Q_0 and Heat Load

Once the maximum gradients have been established, Q_0's are measured for each cavity. Q_0's are calculated from a calorimetric measurement of the power dissipated by the cavity into the helium bath. This is accomplished by isolating the cryomodule from the helium transfer lines and measuring the rate of rise of helium pressure with RF off, known heater power, and finally with RF on. This method can resolve power dissipation as low as 1 Watt.

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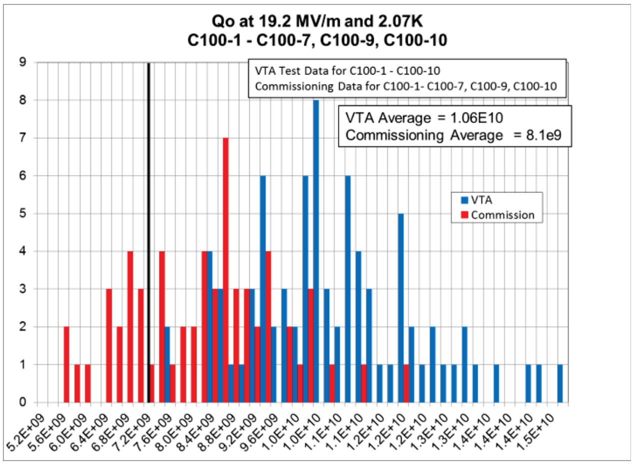

Figure 10: Distribution Q0's at 19.2 MV/m.

The design of this cryomodule calls for a cavity with a Q_0 of 7.2E9 at 19.2 MV/m. Figure 10 illustrates the distribution of Q_0's for both VTA tests and for Commissioning.

The average value for Q0 at 19.2 MV/m is 8.1E9. The percentage difference in the average Q0 values measured in the VTA (1.1E10) and commissioning measurements at 19.2 MV/m is about 26% and represents about 7 W of dissipated power.

It should be noted that while the VTA is able to measure the Q_0 of the individual cavity, measurements made during commissioning are actually measuring the Q_0 of a system that includes the cavity and other components such as the waveguide coupler.

The waveguides were designed for a heat load contribution of less than 3 W (2 W dynamic and 1 W static). A coupler heat load contribution of 1 W would lower the Q_0 of 1.1E10 by about 5%. A contribution of 2 W would lower that value by 10% to 9.95E9. So waveguide heating accounts for only a small reduction in Q_0.

Figure 11 depicts the Q_0 curve for a typical cavity as measured during commissioning and compares those measurements with VTA data. This figure shows good agreement between the two data sets at lower gradients (below 12 MV/m).

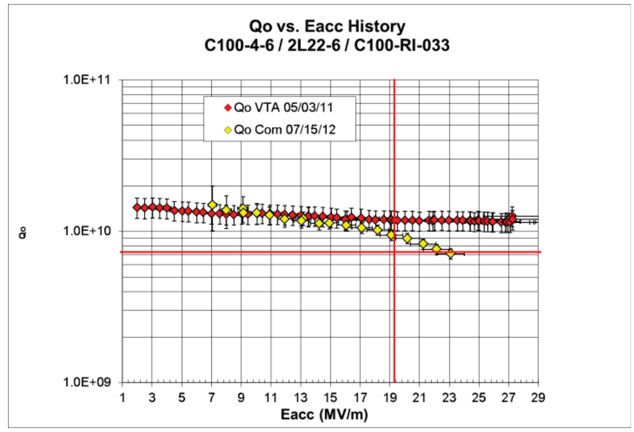

Figure 11: Typical Q0 Curve VTA and Commissioning.

At 19.2 MV/m, the difference between the two datasets is similar to that of the averaged values. In this case, field emission is clearly responsible for most of the reduction in Q_0. It should be noted that even with the added heating terms and higher field emission, this cavity and on average, all of the cavities still exceed the specification for Q_0 and gradient. Finally, Figure 12 shows the distribution of Qo's at 7 MV/m. This figure shows much closer agreement between VTA and commissioning data. Field emission is mostly non-existent at this gradient.

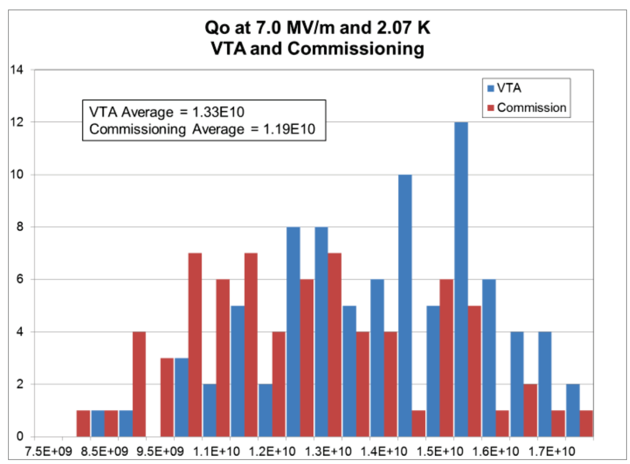

Figure 12: Qo Distribution at 7 MV/m .

Q_0 measurements allow us to determine operating gradients based on a dynamic heat load that does not exceed 29 W per cavity or a combined total of 232 W for the full string. These are the maximum gradients for full eight cavity operation. The average "eight cavity Emaxop" gradient for the nine cryomodules tested so far is 19.6 MV/m.

Table 1: C100 Energy Gains by Cryomodule (MV)

	Commission	Ops
C100-1	104.3	94.5*
C100-2	109.6	108
C100-3	118.4	
C100-4	105.8	
C100-5	109.9	
C100-6	108.2	
C100-7	108.4	
C100-8		
C100-9	113.7	
C100-10	109.8	

Using these gradients, the cryomodules are able to deliver voltages as shown in Table 1. The average energy gain for the C100 cryomodules so far is 110 MV which exceeds the design goal of 108 MV.

Two of the cryomodules have been operated with beam as shown in the table. During the final 6 GeV run, the focus was on learning how to optimize the controls and procedures necessary to control a C100 cavity string at maximum gradients. A decision was made to focus on C100-2. C100-1 was not optimized and was not operated at its full potential. It is expected that C100-1 will soon be operating at the gradients specified during the commissioning process.

Microphonics and Tuning Sensitivity

The 12 GeV project "budgeted" for 25 Hz peak total detuning (4 Hz static plus 21 Hz dynamic) based on the available klystron power (13 kW), the design Q_{ext} (3.2E7) for the fundamental power couplers, and maximum beam load (465 μA) [8].

The measurement of cavity detuning due to external vibration sources and the vibrational modes of the cavity/cryomodule structure is conducted in both the CMTF and in the tunnel.

Microphonics testing of the first unit (C100-1) met design goals marginally, but results were higher than expected based on prototype testing. This unexpected result was due at least in part to the the low loss cell shape used for the C100 cavities. The cell walls are more vertical as they approach the iris making them more susceptible to deflection than the original CEBAF cell shape. Even though the detuning due to microphonics was within the 12 GeV specification, a detailed vibration study was initiated and conducted on the first few cryomodules. This led to a simple modification of the pivot plate in the tuner assembly that reduced the amount of detuning in later cryomodules by an average of 42%.

Figure 13 depicts the frequency shifts due to microphonics over a 90 second period in cavities with and without the modified tuner and shows how the pivot plate was modified. The cavity with the modified tuner shows almost a 50% reduction in detuning.

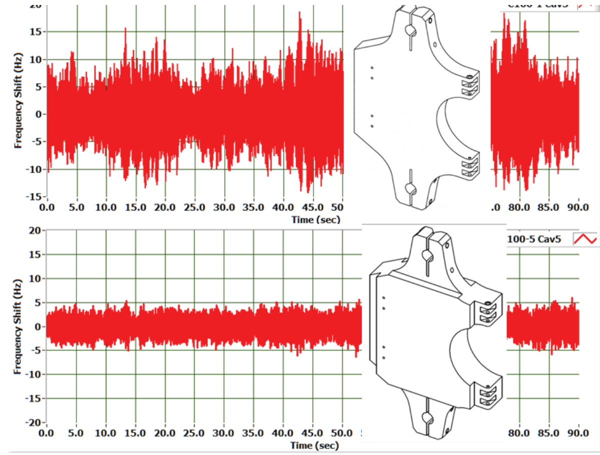

Figure 13: Time Domain Microphonics data Before and After Modification.

Modifying the tuner assembly also led to an average reduction of 35% in the cavity pressure sensitivity (detuning due to pressure changes). An average reduction of 25% in the static Lorentz detuning was measured as well.

OPERATIONAL CHALLENGES

The first two cryomodules were operated continuously from January through the end of the final 6 GeV run, on May 18. Cryomodule voltage ranged from 50 MV to over 100 MV depending on the requirements of the experiments [9].

This run offered an opportunity to develop an understanding of the operational characteristics of the cavity string and tuners as well as LLRF optimisation.

At the end of the run, one of the two cryomodules, C100-2, was operated at 108 MV with full beam loading of 465 uA for more than one hour.

The RF system is completely new for these cryomodules. Each cavity is powered and controlled by one klystron and a LLRF system. The klystrons produce 12 kW of linear power and 13 kW saturated.

The LLRF system consists of the field control chassis (FCC), stepper motor chassis, cavity interlocks, and piezo amplifier [10].

Much of the challenge in operating these cryomodules at high gradients results from the high (3.2E7) Qext's of the Fundamental Power Couplers and the sensitivity of the C100 cavities to detuning. For a cavity with an unmodified tuner, the detuning from the RF off state to 19.2 MV/m would be about 770 Hz while the cavity bandwidth is about 47 Hz.

The first two cryomodules did not have the benefit of tuner modifications, so the peak detuning due to microphonics could run as high as 21 Hz. The unmodified cavities also have an average pressure sensitivity of 350 Hz / torr and an average Static Lorentz detuning in excess of 2 Hz/(MV/m)^2.

The piezo tuner has proven to be very useful in compensating for the slow detuning that might be caused

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by helium pressure drift or slow microphonics. Used in concert with the mechanical tuner, the effect on detuning is dramatic. See Figure 14 for a demonstration of that compensation. Note that the vertical scale for this figure is ± 8 Hz.

Lorentz detuning is responsible for what was referred to as “cavity fratricide”. This would occur when a single cavity faults due to a quench or other cause. A C100 cavity faulting at 20 MV/m could experience approximately 800 Hz of detuning. The mechanical coupling between cavities has been measured to be about 10% and insures that adjacent cavities will also detune by some amount. If there is not enough RF power overhead available to compensate for the detuning, adjacent cavities will also fault and cause a “domino” effect which could shut down the entire cavity string.

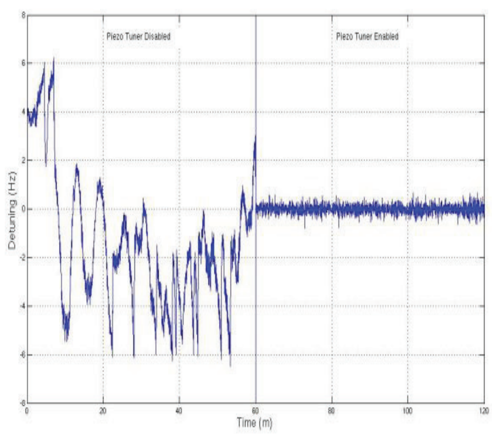

Figure 14: Piezo Compensation.

One way to mitigate the risk of such events is to have the LLRF controls for adjacent cavities switch from the Generator Driven Resonator (GDR) mode to a Self-Excited Loop mode until the faulted cavity is recovered.

The learning process undergone by Jefferson Lab staff led finally to the event pictured in Figure 15. An extended run of a C100 cryomodule at 108 MeV at the full beam loading required for the 12 GeV project, 465 μA.

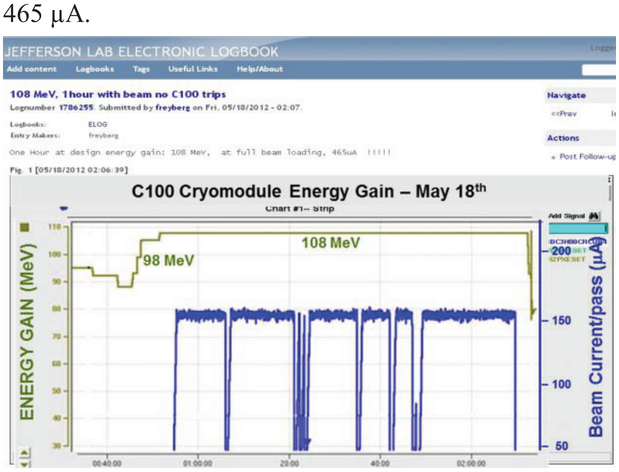

Figure 15: Extended Run at 108 MV and 465 uA.

This goal was reached without the benefit of the improved tuner design.

LESSONS LEARNED

As we near the end of the production phase of the C100 cryomodule project and prepare to move into the operational phase, there are some important points worth noting for future cryomodule projects.

Cavity performance is critical to a successful design. However, the performance of the cavity should not be considered in isolation. The effect on performance of the system (the cryomodule) in which the cavity will be installed must be considered.

It is also important when designing a specification for cavity performance, to take into account potential reductions in performance as the cavity moves through the production process. As an example, the field emission onset gradients are lower for installed cavities than for cavities tested in the VTA. This occurred despite a rigorous quality control program throughout the cryomodule production process. Even with performance reductions, the C100 cryomodules have exceeded their design goals in all respects thanks to performance margins built in to the original design.

While the response of the C100 cavities to microphonics was below the value specified by the 12 GeV project, the 12 GeV project made the decision to invest the time and effort to investigate possible improvements. This investment resulted in large improvements with a simple design change and will result in more robust operations for a cryomodule design that has already proven capable of meeting the design goals.

CONCLUSION

Nine of ten C100 cryomodules have been commissioned in the CEBAF linacs. Commissioning results show that these cryomodules will deliver an average energy gain of 110 MeV which exceeds the design goal of 108 MV. The C100 cavities are able to operate at an average maximum operating gradient of 19.6 MV/m. This exceeds the design gradient for the C100 cavity. Two of the cryomodules have been operated with beam with one operating at the design energy and the full beam loading specified for the 12 GeV project. This goal was reached with a cryomodule that had not been modified for improved microphonics response.

In November, 2013, normal operation of the CEBAF accelerator will resume and it is expected that all of the C100 cryomodules will perform as has been predicted by commissioning tests.

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