OPERATION OF THE CEBAF 100 MV CRYOMODULES*

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) 12 GeV upgrade reached its design energy in December of 2015. Since then CEBAF has been delivering 12 GeV beam to experimental Hall D and 11 GeV to experimental halls A and B in support of Nuclear physics. To meet this energy goal, ten new 100 MV cryomodules (80 cavities) and RF systems were installed in 2013. The superconducting RF cavities are designed to operate CW at a maximum accelerating gradient of 19.3 MV/m. To support the higher gradients and higher Q_L (~ 3×10^7) operations, the RF system uses 13 kW klystrons and digital LLRF to power and control each cavity. This paper reports on the C100 operation and optimization improvements of the RF system and cryomodules.

INTRODUCTION

Since 2014 ten new eight cavity high gradient cryomodules (designated as C100) have been in operation supporting nuclear physics experiments. 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 were designed to have an energy gain of 98 MeV, with an additional 10% overhead reaching 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).

The RF system powering and controlling these cryomodules is also a new design [2]. Like most CW SRF accelerators each cavity is powered and controlled by a single klystron and LLRF system. The klystrons produce 12 kW of linear power. The eight klystrons are self-protected with their own interlocks as part of the high power amplifier system. The LLRF controls down convert from the cavity frequency to an intermediate frequency (70 MHz). The cavity signal is then digitized and processed using an FPGA. 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.

Since 2014 the cryomodules have performed as needed to provide the energy for the experimental program [3, 4]. Table 1 shows the C100 energy contributions from each cryomodule during the spring 2016 operation period comparing them to their commissioned energies. The lower operational energy is due to a number of challenges that have presented themselves in the operation of the C100 cryomodules. The cryomodules have shown themselves to be sensitive to He pressure variations caused by a combination of RF/resistive heat and the heat capacity limitations of the pipe between the individual cavity helium vessel and the, shared two-phase pipe. When the capacity is exceeded there is a pressure transient which leads result in frequency detuning larger than the klystron power can accommodate. Transient vibration induced microphonics from driven external sources (trucks, cooling towers etc.) with frequency content that falls on the modal resonances of the structure can be a source of unwanted trips. Lastly cavity field emission, becoming dark current, has posed both a radiation damage issue with local cabling & magnets and a vacuum issue in the immediate warm regions downstream from the C100 cryomodules. While these issues have been a challenge they have not prevented CEBAF from delivering electrons for Nuclear physics experiments. We report on the problems and mitigations that are being put into place to overcome them.

Table 1: Cryomodule Energy Gains

Cryomodule	Zone	Commissioned Energy	Operational Energy
C100-1	SL24	104 MV	77.1
C100-2	SL25	122	89.6
C100-3	NL22	108	91.2
C100-4	SL22	93	91.5
C100-5	SL23	121	91.9
C100-6	NL23	111	99.4
C100-7	NL24	103	95.9
C100-8	SL26	110	90.7
C100-9	NL25	105	85.0
C100-10	NL26	106	83.5

CRYOGENIC DETUNING

The C100 cryomodule individual cavity helium vessel piping is designed to accommodate up to 52-62 Watts of RF or electric heat at 2.07 K and a total cryomodule heat load of about 350 which is limited by the end can piping. Above 2.0 K the heat capacity limitation is a strong function of the helium pressure. If the heat in an individual vessel reaches the limit for the heat riser pipe, the helium temperature inside the helium vessel exceeds 2.18 K and there is a pressure transient which causes a microphonic perturbation that is enough to detune the cavity beyond what the klystron can accommodate. In addition the He pressure increases slightly down the LINAC (the C100s are at the end) so the cryomodules at the end of the linac can't

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handle as much heat because the return pressure is higher. (see Fig. 1).

The initial system design had one heater power supply per cryomodule. A new8-channel heater power supplies have been designed and will be installed in the coming months. This will allow improved heat control and will further reduce heat riser choke issues.

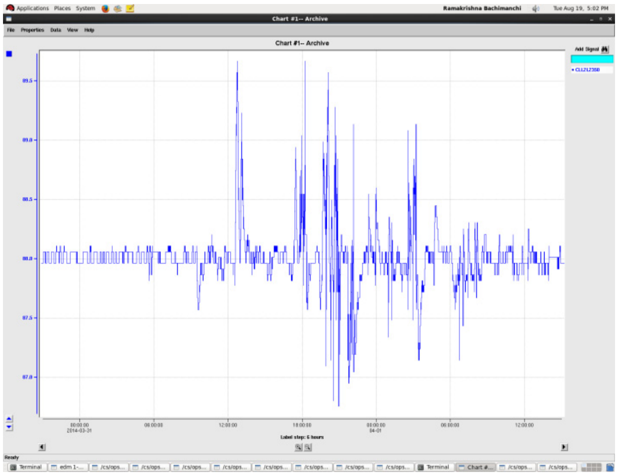

Figure 1: He liquid level in a cryomodule during a heat riser choke event.

CAVITY MICROPHONICS

The C100 cryomodule have shown a susceptibility to external microphonic perturbations. Ground transmissions from trucks, construction equipment, large cooling tower fans and thunder have been shown to detune the C100 cavities to the level where there are problems. This has been known for some time, though its impact on operations is just now being understood. Initial tests show that the perturbations are transmitted into the cryomodule primarily through the waveguides and cryogenic piping. Additionally, the tuner assembly is also susceptible to vibrations. A stiffer tuner pivot plate was added during construction on the last seven cryomodules which reduced the average detuning from ~ 3 Hz rms. down to 1.5 Hz rms. [4]. Still the modified cryomodules are susceptible to external perturbations which can trip the cavities off.

Recently mitigation efforts to reduce microphonic effects on C100 cryomodules have been implemented. Figure 2 shows the RF detune phase for two cryomodules (cavities 1-4) as a nitrogen delivery truck was driven slowly by the service building above the tunnel. SL24 is a "hardened" zone that has extra waveguide bracing/damping and an external damper assembly on the tuner. SL25 has no improvements. Both cryomodules have the original tuner pivot plate. The improvement between the hardened and non-hardened cryomodule is approximately a 40% reduction in microphonics rms. as well as a 40% reduction in susceptibility to events such as the truck driving by.

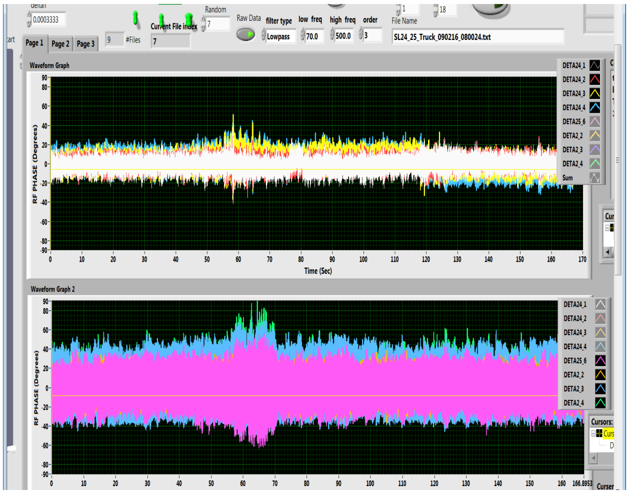

Figure 2: RF detune phase for cavities 1, 2, 3 and 4 for the hardened zone SL24 (upper) and original SL 25 (lower). A liquid nitrogen truck drove down the south linac service road at about 10 mph passing the zone at time equals about 30 seconds.

CAVITY FIELD EMISSION

The elevated gradients (> 12 MV/m) of the C100 cryomodule can produce field emitted electrons with enough energy such that Bremsstrahlung X-rays can in turn produce neutrons via (gamma, n) reaction.. The effect is threefold. First there is the possibility to damage external components, second is the activation of the cryomodules and nearby warm beam lines and third is the increased cryogenic heating from the added electron load. Complicating this is that the electrons can be captured in adjacent cavities and accelerated down the linac radiating beam elements at the end the linac.

During cavity commissioning the cavities are tested to find the field emission onset (~1 mR/hr). The average for the 80 C100 cavities was 13 MV/m. Figure 3 shows the results of a typical cavity field emission test.

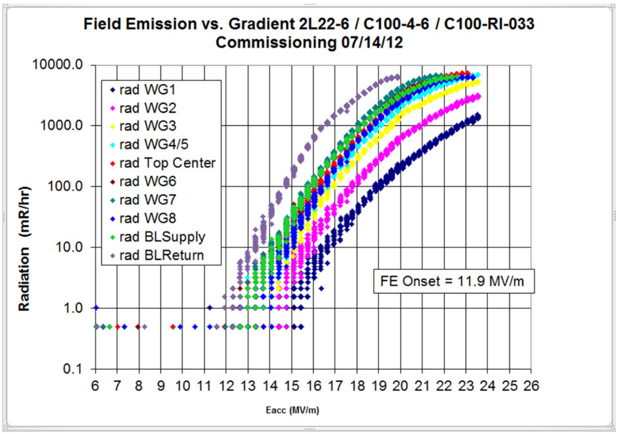

Figure 3: Field emission onset of a C100 Cavity. The curves represent the 10 GM tubes.

Recent tests have shown that cavities operating well above field emission onset can have radiation levels in excess of 10's to 100's of R/hr in the warm girder region between cryomodules. There is a consensus that field emitted electrons are captured and accelerated by other cavities in the cryomodule. They are then intercepted where the cavity aperture steps down to the warm section beam pipe producing a shower of radiation. The induced radiation outside of C100-10 was causing vacuum trips. Figure 4 shows the radiation damage to coaxial cables just outside of the cryomodule.

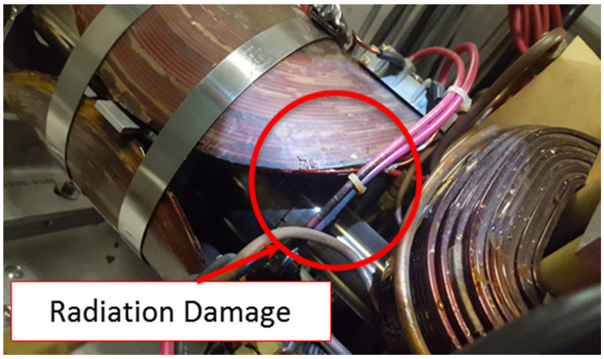

Figure 4: Showing effects of field emission induced radiation.

Initial mitigation was to turn the cavity gradients down to lessen the radiation load. This is the main reason that C100-10 energy gain is much less than the other C100s. Additionally, cavities with early field emission onset are being helium processed.

For the longer term, a model is being developed from commissioning and operational radiation data. It will also incorporate direction and multiple cavity effects on the field emitted electrons. The goal is to have a realistic method of optimizing the gradients while keeping the radiation load at an acceptable limit.

Additionally, and as a consequence of the impact field emission is having on operations, procedures are being improved to ensure the lowest possible particle contamination when installing or removing a cryomodule [5].

OPERATIONAL IMPROVEMENTS

Operational improvements to the RF control have been an ongoing process since commissioning. Enhancements include: an automated process to recover C100 cavities, improved fault logging and data collection and implementing piezo tuners on the four of the cryomodules most susceptible to microphonics.

A source of accelerator down time is the time it takes to recover a C100 cryomodule after a fault. The automated recovery application will shorten the time to recover a C100 cavity and or cryomodule by eliminating the need for an operator to initiate cryomodule recovery. Because of the strong mechanical coupling between cavities, the Lorentz detuning that takes place when a cavity faults can bring down the whole zone tripping off the electron beam. The newer algorithm will sense this detuning and turn the cavities to the free running self-excited loop (SEL) mode which follows the cavity as it detunes. Once the disturbance is over the cavity/s will lock back to the master reference. An operator can now turn beam back on. The goal is that no human intervention with the RF system would be required.

Piezo tuner (PZT) capability was designed into the C100 cryomodules but never implemented beyond initial tests. The impact on using the PZTs to compensate for slow (< Hz) detuning like He pressure variations is substantial. Figure 5 shows the cavity detuning with and without the PZT turned on while locked in GDR mode.

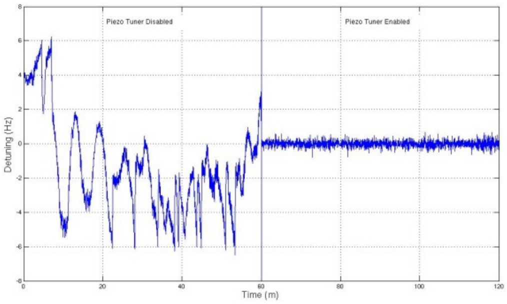

Figure 5: PZT off vs. on. Note that the full range on the x-axis is 120 minutes

The four non-stiffened tuner C100s, which are more susceptible to microphonics, will be outfitted with piezo tuners this fall. The thought is that with the piezo tuners operating, the stepper motors will not run as much keeping the cavities closer to the reference frequency and making more RF headroom available for microphonic detuning.

SUMMARY

The ten CEBAF 100 MV cryomodules have been successfully operated for nuclear physics experiments over the past two years. C100 cryomodule energies have been less than the commissioned energies due to a variety of issues. Opportunistic testing is taking place to better understand some of the issues. Mitigation efforts (waveguide and tuner stiffening, improved cryomodule heat control, field emission modelling, and RF control improvements) are being implemented to get the C100s back to their commissioned energy.

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