COMMISSIONING AND OPERATION OF THE CEBAF 100 MV 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 and RF systems. 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), a new RF system has been developed and is being installed to power and control the cavities. The RF system employs digital control and 13 kW klystrons. Recently, two of these cryomodules and associated RF hardware and software have been installed and commissioned in the CEBAF accelerator. Electrons at linac currents up to 540 μA have been successfully accelerated and used for nuclear physics experiments. This paper reports on the commissioning and operation of the RF system and cryomodules.

INTRODUCTION

In August of 2011 two new eight cavity high gradient cryomdules were installed 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).

The RF system is completely new for these cryomodules [2, 3]. Each cavity is powered and controlled by one 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. The cavity field and resonance control PID algorithm is contained in one large 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.

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RF SYSTEM/CRYOMODULE COMMISSIONING

The RF systems and cryomodules are commissioned in series. First the RF control and RF power systems are tested. Next the cryomodule is attached to the waveguides and commissioned. Lastly the RF system is optimized and then handed over to operations. The digital RF control has made testing much simpler and easier since replaces the RF sources and analog phase lock loops used in the past.

The RF power systems are tested by placing shorting plates across the waveguide ends and powering the klystrons up to their saturated power level of 13 kW. While the klystrons have previously been tested, the circulators and waveguide directional couplers have not been tested. High power testing is accomplished using the LLRF system in "tone" mode. Tone mode allows the LLRF system to output a single frequency at selectable amplitudes. At this time forward and reflected power cables are calibrated, and their attenuations are loaded into the EPICS control system.

The LLRF system consists of the field control chassis (FCC), stepper motor chassis, cavity interlocks, and piezo amplifier [2]. The FCC is tested and calibrated on a separate test stand before installation into the accelerator. All other subsystems are bench tested before installation. The FCC is loop backed on itself through the reflected power coupler and operated in Generator Driven Resonator (GDR) mode. An IIR filter inside the loop is set to mimic the cavity by setting the roll-off frequency to approximately 35 Hz. In this manner the controls can be tested in place.

A key step before high power cavity operation is the cavity interlock check out. Each cavity has one arc detector, two IR sensors, waveguide vacuum monitor (between the two windows at the cryomodule), a quench detector, and beam line vacuum. The functionality of every interlock is tested to insure that RF is shut off in event of a fault. Cavity testing cannot start until this procedure has been completed and signed off. Once the RF system has been fully operated and the system calibrated, it is ready for the cryomodule.

Cryomodule Commissioning

All cavity/cryomodule performance aspects are tested in the CEBAF tunnel as part of commissioning [1]. The cavities are first tuned to the reference frequency at low power. The LLRF system is placed in SEL mode and used as the signal source. Both the stepper and the PZT are tested and measured. The PZT is tested for maximum stroke; design is 2 kHz at 150 VDC. With the stepper motor, the cavity is tuned from stop to stop and tuner hysteresis is measured. The Q_{ext} of the fundamental power coupler is calculated from the decay time of the emitted power using pulsed RF. The gradient is recorded for threshold (minimum detectable response from GM tubes) cavity field emission turn on. The Q_o of each cavity is also measured so that heat load is known and can be dynamically calculated depending on the gradient. Each cavity's maximum useable operational gradient is determined. Typical limitations include, quench, He boiling, and waveguide vacuum. Finally, all eight cavities are run together to insure they can operate at the gradients predicted by heat load measurements.

Once cryomodule commissioning is complete, the RF control system PID gain settings are optimized and the cavity gradient calibrations are uploaded.

OPERATION AND CONTROL

The two cryomodules were operated continuously from January through the end of the run, on May 18. 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.

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 gradients we intend to run at, 20 MV/m, detuning is 800 Hz from RF off to RF on. The typical method for recovering a Lorentz detuned cavity is to use a PZT and compensate turn on. At JLab we have gone in a different direction and employ a digital SEL that tracks the cavity up to the operational gradient. A firmware application then switches to GDR mode, locking the cavity to the reference. Figure 1 shows plot of the forward power/phase and I/Q signals as it is switched from SEL to GDR.

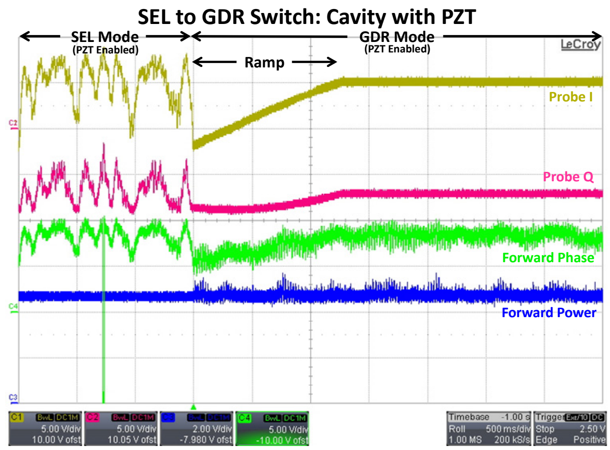

Figure 1: Transition from SEL to GDR.

Cavity faults in the cryomodule present another operational challenge. The mechanical coupling between adjacent cavities is roughly 10%. 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. The klystron does not have the overhead at higher gradients to compensate for such a detuning. To keep the adjacent cavities at gradient, when a cavity trips off, they are immediately switched to SEL. Once the faulted cavity is cleared and brought to gradient, all the cavities are switched back to GDR using an EPICS application.

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 2 shows the detuning in Hz for rms. and peak for a typical cavity.

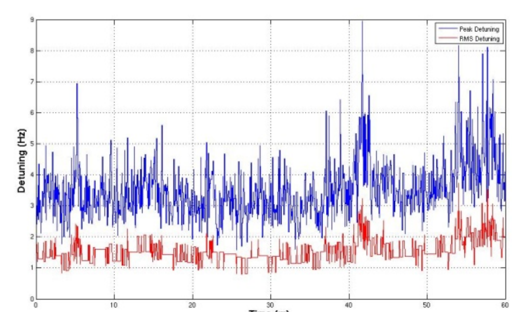

Figure 2: Rms. average and peak microphonic detuning of a cavity.

A useful feature possible on digital LLRF control systems is the use of data buffers. The hardware allows the operator to catch real time data from the cavity-control system. This is extremely useful when diagnosing cavity faults or measuring microphonics. Figure 3 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

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(Lorentz contraction from the faulted cavity) of the non-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.

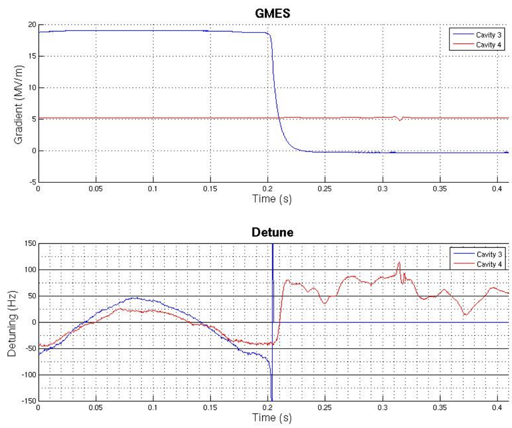

Figure 3: Graph of gradient and detuning (Hz) as a cavity is faulting (blue).

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 4 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. The PZT voltage is centered at 75 volts, for a full range of 150 volts. If the voltage goes above or below a certain voltage the stepper turns on to "re-center" the PZT back to 75 volts. It is intended that in the future a more sophisticated control algorithm will be employed taking into account the cavity mechanical resonances.

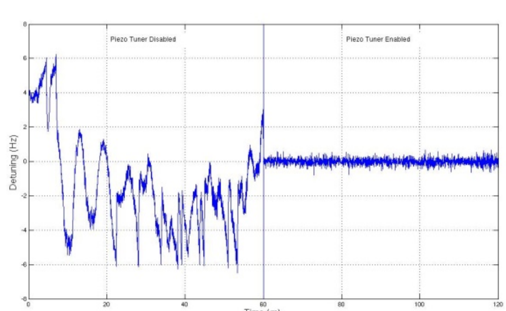

Figure 4: PZT off vs. on.

HIGH GRADIENT OPERATION/TESTS

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 need 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. On May 18, 2012 we achieved 108 MV for over an hour at 465 µA.

SUMMARY

The CEBAF 100 MV cryomodules have been successfully tested and operated for nuclear physics experiments. Cryomodule energies up to 108 MeV and cavity gradients over 20 MV/m have been run CW for over an hour with no faults. The RF system (power and control) has met its performance specifications. The remaining eight cryomodules and RF systems for the 12 GeV energy upgrade will be installed in the next year.

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