# STATUS OF THE CEBAF ENERGY UPGRADE RF CONTROL SYSTEM *

C. Hovater, T. Allison, R. Bachimanchi, G. Lahti, J. Musson, T. Plawski, C. Seaton, D. Seidman
Jefferson Lab, Newport News Virginia, 23606

*Abstract*

To support the CEBAF energy upgrade from 6 GeV to 12 GeV, the RF control system is being modernized to control the high gradient high $Q_L$ superconducting cavities. Eighty new LLRF systems are being built to support the upgrade. The new system incorporates a heterodyne transceiver along with I&Q sampling to measure and control magnitude and phase. A low-cost Altera FPGA is used to digitally implement the cavity control algorithms. One of the features of the system is a digital self excited loop to track the cavity over large Lorentz detuning (800 Hz) during turn on. The system has successfully completed preliminary development and is now moving into the production stage of the project. This paper discusses the design, modeling, testing and production of the new RF control system and associated peripheral systems (cavity interlocks, and resonance control).

## INTRODUCTION

In the next two years the CEBAF accelerator will increase its final beam energy from 6 GeV to 12 Gev. To accomplish this, 10 new eight cavity cryodmodules are being constructed. To meet the increased energy, each new cavity will have an average gradient of approximately 20 MV/m. While the overall field control specification remains unchanged for the upgrade cryomodules, the higher gradients require 13 kW klystrons to be purchased. The RF control system is also being modernized by going to a digital based controller. In addition other aspects of the RF system including the resonance control system, the cavity interlocks, and the high power amplifier controller have been redesigned to take advantage of technology advances.

The new cavities pose some challenges (Lorentz detuning) that have not been seen operating the lower gradient cavities. Since Lorentz detuning goes as the square of the gradient the new cavities may have a detuning approaching 800 Hz or 16 bandwidths, from 0 gradient to the operating gradient. To quickly recover a cavity we use a self excited loop (SEL) that has been programmed into the firmware [1]. Once back at gradient the control system is switched back to Generator Driven Resonator (GDR) controller. The recovery speed is the speed of the cavity fill time plus the time it takes to switch from SEL to GDR, ~ 10 ms.

## FIELD CONTROL

The field control system architecture is a typical modern LLRF design with one large FPGA board (digital) connected to a transceiver board (four receiver channels and one transmitter channel). Figure 1 shows the field control chassis (FCC). The interface to the EPICS control system is through an off the shelf PC104 board which also acts as the EPICS Input-output controller (IOC). In addition the chassis has numerous I/O signals to interface to other systems (e.g., resonance control, high power amplifier, machine protection, beam based feedback and timing control).

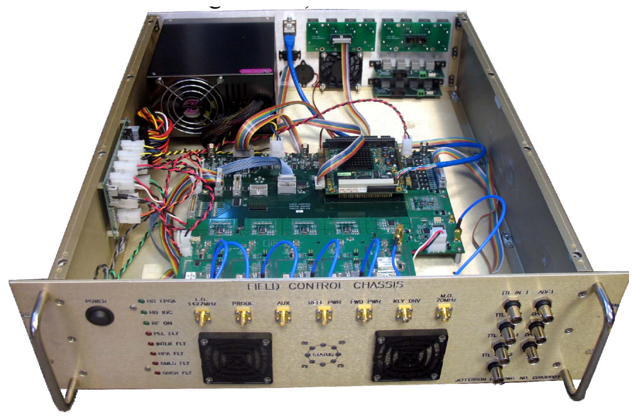


Figure 1: Field Control Chassis

The transceiver board converts the cavity frequency, 1497 MHz, down to an intermediate frequency (IF) of 70 MHz (which is a legacy frequency). The IF is digitized using 16 bit ADC's. 16 bit ADC's are necessary to keep the field regulation specification (0.5$^{o}$ and 4.4x10$^{-4}$) over a dynamic range requirement of 20 dB. Channel to channel isolation is 60 dB between forward power and reflected power and 70 dB between cavity transmitted and all other channels. Since the transceiver board is separate from the digital board the digital board can be used for other frequencies while only changing the transceiver board.

The digital board implements the field control algorithms using an Altera Cyclone III FPGA. A 70 MHz reference is fed to an on-board phase lock loop (PLL) to generate a 56 MHz clock that drives the ADCs, DAC and FPGA. Under-sampling the 70 MHz IF at 56 Msps yields the in-phase and quadrature (I&Q) components of the signal for digital signal processing by the FPGA firmware. The DAC channel uses I&Q values to generate a 14 MHz sine wave with a 56 MHz update rate. This also produces a 70 MHz component that is filtered and amplified for use as the cavity drive. The digital board also has a 1 Msps 16-bit DAC used to drive a piezo tuner and 4 more DAC channels for diagnostics. These diagnostic DACs have proven useful for monitoring control algorithm signals during development. A 1 Msps 16-bit ADC used to measure the local oscillator (LO)

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power and two more ADC channels are available for future applications. SDRAM is used for capturing circular buffer waveforms of important signals for diagnostics.

## RESONANCE CONTROL

With the higher gradients the new cryomodule poses a challenge for an RF system to recover cavities after a fault. The cavity with zero gradient maybe detuned 800 Hz from an operational gradient of 20 MV/m. Other accelerators have employed a Piezo tuner (PZT) to quickly adjust the cavity as the gradient is ramped up [2]. We intend to use a self excited loop to bring the cavity back to the operational gradient and then lock the cavity to the reference. A PZT will be used to minimize effects of helium drifts and keep the cavity frequency close to the reference. The PZT tuning range is 2000 Hz. For larger detuning, a stepper motor will be used to recover from cryogenic trips and long maintenance downs. The stepper can cover +/- 200 kHz.

The field control chassis will supply the resonance control with detuning information. When in the GDR mode, the FCC will provide the tuners with a traditional cavity transfer function phase to keep the cavities close to the reference. When the FCC is in SEL mode and is recovering cavities detuned more than a bandwidth, a frequency discriminator (a byproduct of the SEL firmware) provides tuning information.

The stepper motor chassis controls eight stepper motors. It uses an off the shelf micro-stepping motor driver (US Digital MD2S). Like the field control chassis the stepper chassis uses a custom FPGA based motherboard and a PC104 EPICS IOC. Cavity tuning information is delivered through the control network from the FCC. Figure 2 shows the stepper motor chassis.

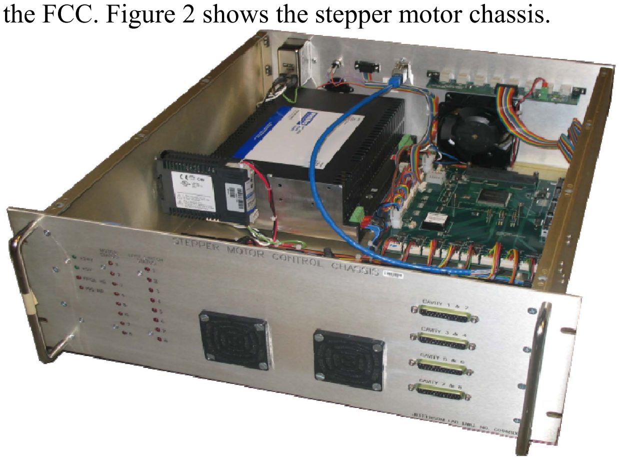


Figure 2: Stepper motor control chassis

The PZT amplifier incorporates an Apex amplifier (PA69) normally used for printers and copiers. The amplifier can provide 150 V/30 mA with a bandwidth of 10 Hz, full scale. Typically the system will need to provide approximately 20 V at 10 mA at 10 Hz. The PZT is controlled by the FCC using one of its 0-10 vdc DACs. Figure 3 shows the PZT chassis and one of the driver cards.

## CAVITY INTERLOCKS

The superconducting cryomodule requires a number of protection interlocks. Table 1 shows the different cavity interlocks. The interlocks are similar to what is on the present CEBAF cryomodules.

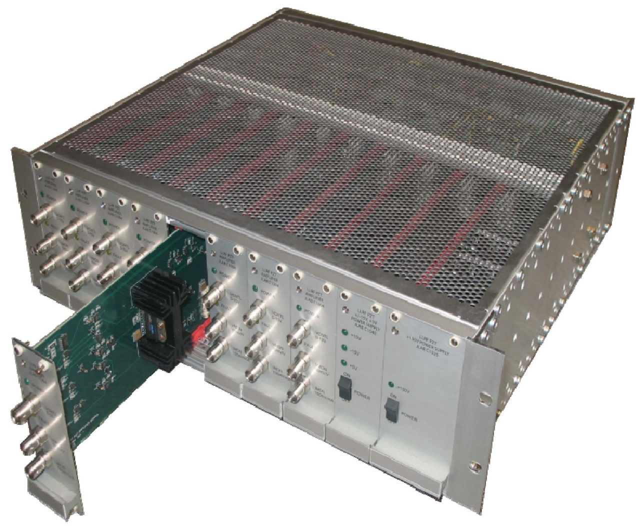

Figure 3: Piezo Tuner amplifier chassis

Table 1: Cavity Interlocks

| **Interlock** | **Detection** | **System** |
|---|---|---|
| Arc | Photo-multiplier | Interlock chassis |
| Infrared | Thermopile | Interlock chassis |
| Waveguide Vacuum | Ion Pump | Interlock chassis |
| Beam Line Vacuum | Ion Pump | Interlock chassis |
| Quench | Gradient rate change FCC | FCC |

The cavity arc detector consists of a photomultiplier tube mounted at a point on the waveguide entering the cryomodule such that it can view the cold waveguide window. The arc trip window can be adjusted between 10 µs to 10ms. Typically this is set for a trip point of 500 µs. The arc detector is continuously tested automatically using an LED. Any malfunction is reported and the cavity is turned off. There are two IR detectors positioned to view the warm and cold waveguide windows. The IR sensor voltage is recorded cold and then a set point is set up to trigger a fault. Like the arc detector, the IR sensor is also automatically tested. Both the waveguide and beam line vacuum space is monitored with ion pumps and appropriate trip settings established. The quench and RF interlocks are internally developed in the FCC. The quench is a rate of change detector that monitors the cavity field level.

An interlock chassis, similar to the stepper controller, is being designed and will actively monitor all eight cavities in a cryomodule. An additional feature will be a touch screen interface for local control and monitoring. The interface between the interlock chassis and the FCC will be a fiber link, to quickly shut down the RF.

## TEST STANDS

As part of system quality control, each board and field control chassis will be rigorously tested before being installed in the accelerator. In the case of the digital board for the field control, a bed-of-nails test will be used to test all RF receiver ADCs, transmitter DAC and all other I/O (analog, digital, optical). Figure 4 shows the bed of nails test stand.

Once the RF and digital boards are mated together in a chassis they will be tested in the field control test stand. Here the receivers are calibrated using a power meter to ensure precise gradient accuracy during operations. The chassis is then tested around a cavity emulator so that feedback control can be checked and gains set.

Figure 4: Digital board "bed of Nails" test stand

## RECENT CAVITY TESTS

We have been exploring the concept of using the LLRF system for commissioning the superconducting cavities. When cavities are delivered to the accelerator, a number of performance tests are made. These tests include $Q_L$, $Q_o$, tuning range, tuner hysteresis, maximum gradient, cavity microphonics, quench and field emission thresholds. In the past this has required numerous pieces of test equipment, typically operated manually. With the new LLRF system it may be possible to eliminate some of the test equipment and automate these tests.

To this end we recently tested the feasibility of using the new RF system for such measurements. Tuning information is critical for operations. In the past one used a PLL-VCO to determine the mechanical tuning range of the cavity. With the new system, operating in SEL mode, the tuner can be swept stop to stop and the complete tuner range measured. The frequency discriminator will indicate the exact stop frequency. Hysteresis can similarly be measured for both the stepper motor and the PZT. Tuning resolution is better than a Hz. Figure 5 shows the tuning resolution with the RF system.

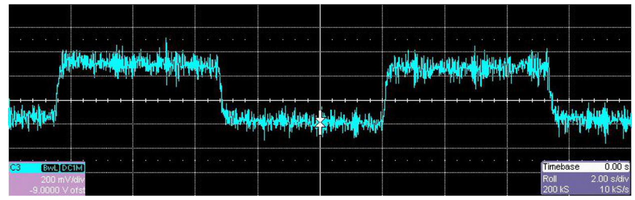


Figure 5: Field Control Chassis diagnostic output (DAC) of the detectable tuning resolution. Cavity was tuned back and forth in 1 Hz steps using the stepper motor.

Other measurements such as cavity $Q_L$ are easily made using a pulsed RF system. From the cavity decay time, loaded Qs can be measured using the waveforms acquired internally by the RF controller. Figure 6 shows the pulsed waveform of the cavity transmitted power that was internally pulsed by the LLRF system.

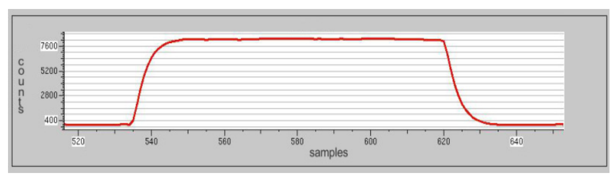


Figure 6: Pulsed waveform of the cavity transmitted power. The vertical scale is ADC counts and the horizontal is samples where one sample is 1.17 ms. Cavity gradient was 7 MV/m.

## SUMMARY

We have successfully transitioned from prototype/development to production. To overcome Lorentz detuning a digital SEL algorithm is being implemented to recover faulted cavities quickly. The new system has been tested on numerous cavities over the last three years. Field control has been tested to 20 MV/m and has met the required amplitude and phase specification [3]. The new digital RF controls will allow flexibility and better diagnostics than the present system. The new LLRF system will also be easier to maintain than the older analog control system. RF and cryomodule commissioning is scheduled to begin summer 2011. All 10 new RF zones will be operational by 2013.

## REFERENCES

[1] C. Hovater et al, "A Digital Self Excited Loop for Accelerating Cavity Field Control," PAC'07, Albuquerque USA, June 2007, WEPMS065, p. 2490.

[2] M. Liepe et al, "Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner," PAC'01, Chicago USA, June 2001

[3] C. Hovater, "RF Control of High QL Superconducting Cavities", LINAC'08, Victoria Canada, September 2008, WE105