LLRF SYSTEM FOR THE CEBAF SEPARATOR UPGRADE*

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) energy upgrade from 6 GeV to 12 GeV includes the installation of four new 748.5 MHz normal conducting deflecting cavities in the 5th pass extraction region. This system will work together with the existing 499 MHz RF Separator in order to allow simultaneous delivery of the beam to four CEBAF experimental halls. The RF system employs two digital LLRF systems controlling four cavities in a vector sum. Cavity tune information of the individual cavities is also obtained using a multiplexing scheme of the forward and reflected RF signals. In this paper we will present detailed LLRF design and the current status of the CEBAF 748.5/499 MHz beam extraction system.

INTRODUCTION

The original beam extraction configuration, allowing simultaneous beam delivery to three experimental halls A, B and C, was designed over 20 years ago. The CEBAF photo-cathode injector produces three interleaving bunches at 499 MHz, hence the operating frequency of the linacs is 1497 MHz. Such a configuration allows extraction of a single bunch out of the three bunches at the end of each pass and directs it to one of the three halls or separates all three bunches at the highest pass [1]

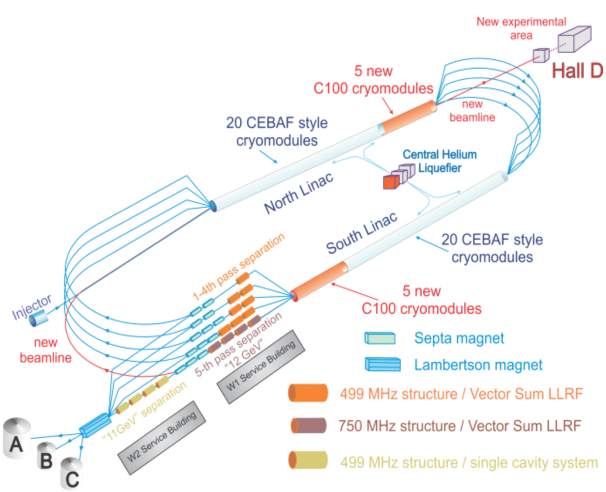

Figure 1: Layout of the 12 GeV CEBAF accelerator

As a part of the 12 GeV Upgrade project, a new experimental hall "D" has been added along with new arc beam line (see Figure 1). This hall will receive the highest energy beam, which comes from the 5th pass separation [2]. Because the existing 499 MHz extraction system only allows bunches to three halls, a new 5th pass extraction system and consequently a new bunch pattern was conceived in order to deliver simultaneous beam to all four halls [3]. A major change in the new separation system is the 5th pass extraction running at 748.5 MHz instead of 499 MHz. The trade-off will be a lower bunch repetition rate because the 5th pass beams for all halls have to operate at 249.5 MHz.

The new beam extraction system requires a number of additional 499 MHz and 748.5 MHz separator cavities to be installed along with new high power RF amplifiers and LLRF systems [4]. To support both 499 MHz and 748.5 MHz LLRF operation a new Separator MO (Master Oscillator) has also been built and installed.

As shown in Figure 1, sixteen deflecting cavities are installed. The first pass has one 499 MHz cavity and one RF system while pass 2, 3 and 4 will use multiple cavities with one RF system, utilizing vector sum control to stabilize the electromagnetic field. Pass 5 has four 748.5 MHz cavities installed and will be driven by one high power amplifier. An additional four 499 MHz cavities have recently been installed on the so called "11 GeV" beam line in order to separate beam among original halls A, B and C. This part of the beam extraction system applies one cavity/one RF source system topology. The separator master oscillator, installed in the W1 service building provides 429 MHz and 678.5 MHz LO signals for RF front-end heterodyning and 70 MHz for the clock reference.

11 GeV SEPARATION SYSTEM

The 5th pass (12 GeV) separation does not separate beams for halls A, B and C. Therefore it was necessary to add a new deflection system on the 11 GeV beam line. It consists of four 499 MHz normal conducting cavities, identical to existing ones. Each cavity has its own high power, solid state amplifier capable delivering up to 10 kW (saturated) of RF power and controlled by a single field control chassis (see Figure 2). These cavities are expected to provide a 499 MHz transverse deflection to the electron bunch train. The requirement is to have the beams to hall A, B and C vertically separated by +17, 0 and -17 mm respectively at the input to the Lamberstson style magnet located 42 m

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downstream from 11 GeV separation. This imposes a beam deflection angle of 260 μradians. In the initial design [5], a 455 μrad kick was required along with eight deflecting cavities. Recent changes in the beam optics design have reduced the kick to 260 μrad and the number of deflecting cavities to four [6]. This was achieved by designing different vertical beam defocusing provided by a magnetic quadrapole upstream of the cavities. The RF power required for separation can be calculated using the following equation:

$$P = \frac{\left(\frac{E_b \times \theta}{sin\varphi}\right)^2}{n \times R_{sh}}$$

where E_b is the beam energy, θ is the transverse kick in radians, φ is the phase between electron bunch and cavity field phase, n is the number of cavities, and R_{sh} is cavity shunt impedance in ohms. For R_{sh} equal to 210 MΩ, a beam energy of 11 GeV and bunches entering the cavity at 60 degrees off crest, the total power required to produce a 260 μradian kick is 13 kW, or 3.3 kW per cavity. The installed 10 kW amplifiers have large headroom, allowing up to 400 μradians deflection of 11 GeV beam.

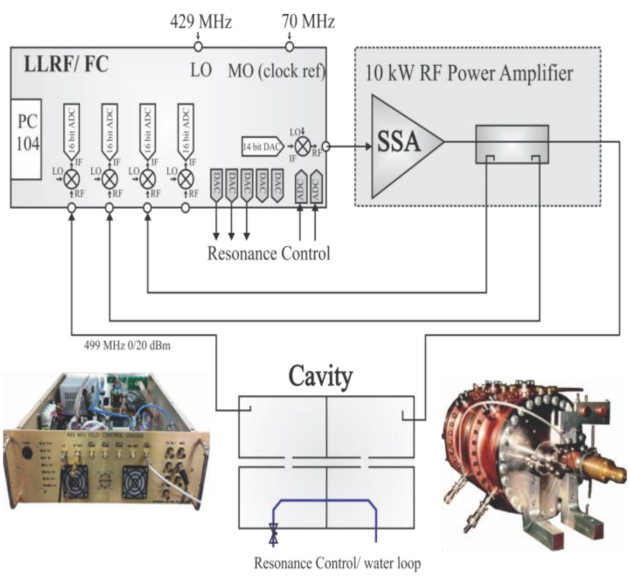

Figure 2: Single source/single cavity for extraction system

Each cavity is controlled by a single LLRF system, called here FCC (Field Control Chassis). As shown in Figure 3, an FCC contains five fast ADC channels (receivers), although one receiver channel has no heterodyning front-end in order to direct sample 70 MHz external clock reference. All RF signals, once down-converted and digitized, are processed in an FPGA. Resulting I and Q signals drive the high power amplifier via a single fast DAC output [4]. The FCC [Figure 4] requires an external 20 dBm LO (429 or 678.5 MHz) and external 3 dBm clock reference (70 MHz). The clock system has a programmable digital PLL and can work with different references as well as produce assorted sampling frequencies.

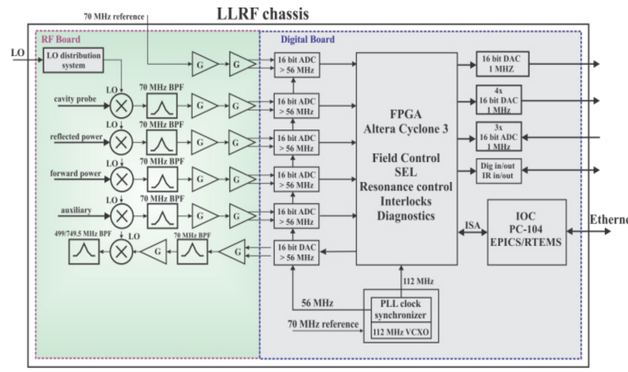

Figure 3: LLRF architecture

The developed firmware supports mainly GDR (Generator Driven Resonator) mode of operation although other modes like tone or SEL (Self Excited Loop) are also available.

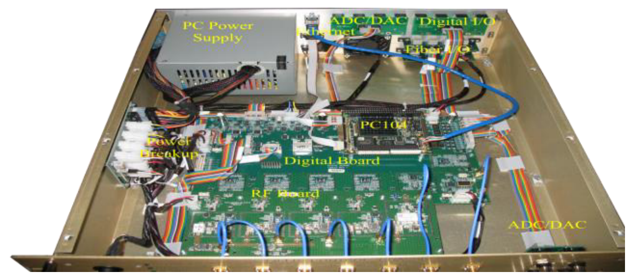

Figure 4: Field control chassis

The communication with the Jefferson Lab EPICS control system is accomplished by an embedded PC104 board (EPICS I/O controller). The FCC is equipped with a number of slow (1MS/S) ADCs and DACs as well as digital (opto-isolated) I/Os, which will be used for cavity resonance control and machine protection. Figure 5 shows the RF system for 11 GeV beam separation during construction and testing.

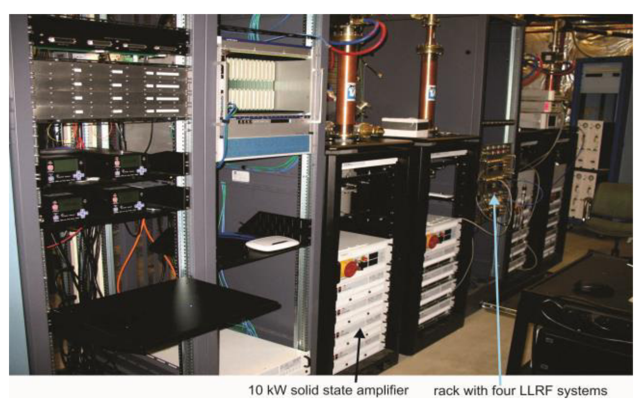

Figure 5: 11 GeV Separator service building

Pass 1-5 SEPARATION SYSTEM

Different from the 11 GeV separation, each pass, 1 through 5, has only one RF power amplifier (IOT). Therefore it is necessary for the multiple cavity systems to use vector sum control [see Figure 6]. Moreover, each FCC will monitor forward and reflected power signals from the cavities and IOT's directional couplers. It means one FCC will have to measure up to four cavity probe signals and/or up to ten forward and reflected signals. Since only four receivers per FCC are available, it was necessary to adopt an RF multiplexer for signals other than cavity probe. The RF multiplexer (see Figure **7**) allows switching between channels with frequency up to 100 kHz. In reality, much slower speed is required because of slow tuning mechanism (temperature/water). Measured channel to channel isolation for RF multiplexer (adjacent inputs) exceeds 80 dB. The same figure shows 748.5 MHz RF board mounted on the top of FPGA based digital platform. In Figure 6 simplified block diagram of one LLRF system controlling up to three cavities is shown.

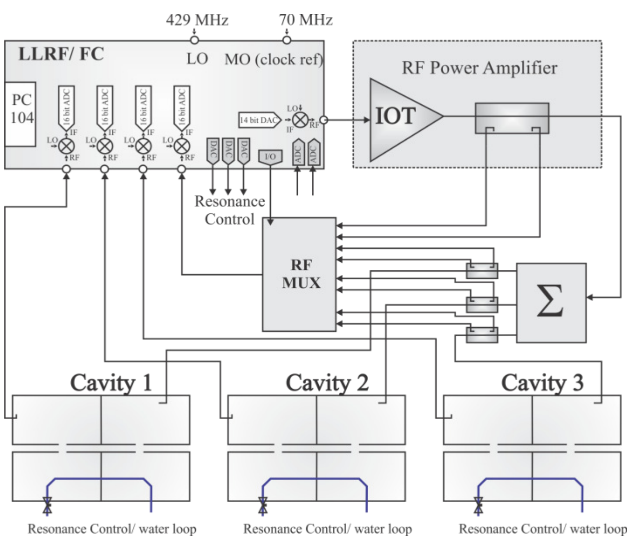

Figure 6: Vector sum architecture

As mentioned before, the 5th pass requires four separator cavities. To solve the insufficient number of receiver channels issue, it was decided to use one FCC to measure only cavity probe signals and drive a single IOT, while a second FCC along with the RF multiplexer is used to monitor all forward and reflected signals as well as control cavities resonance.

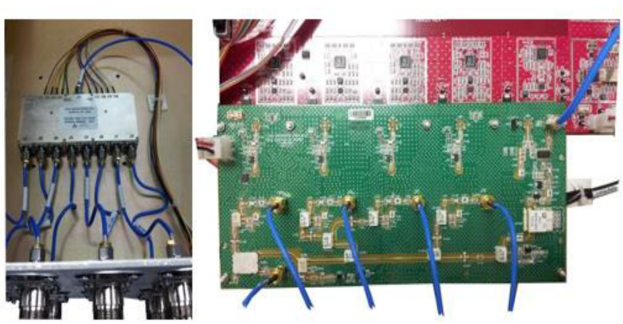

Figure 7: RF multiplexer and 748.5 MHz RF board

The FCCs are equipped with fiber links which will allow the exchange of information between the two chassis (measured angle between cavity probe vector and forward signal vector) to meet control system needs.

CONCLUSION

All presented RF systems have been designed, manufactured and tested. We have developed new firmware to control separator cavities in two modes: as a single cavity and single source or multiple cavities with one RF source. Preliminary stability tests demonstrated satisfactory results for both cases. New EPICS software supporting control system is under development and is expected to be fully functional in September 2014.

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