COMMISSIONING AND PERFORMANCE OF THE BNL EBIS LLRF SYSTEM*

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Abstract

The Electron Beam Ion Source (EBIS) [1] LLRF system utilizes the RHIC LLRF upgrade platform [2, 3] to achieve the required functionality and flexibility. The LLRF system provides drive to the EBIS high-level RF system, employs I-Q feedback to provide required amplitude and phase stability, and implements a cavity resonance control scheme. The embedded system [3] provides the interface to the existing Controls System [4], making remote system control and diagnostics possible. The flexibility of the system allows us to reuse VHDL codes, develop new functionalities, improve current designs, and implement new features with relative ease. In this paper, we will discuss the commissioning process, issues encountered, and performance of the system.

INTRODUCTION

The EBIS RF system consists of the LLRF system, HLRF system, RF structures (Beam Bunchers, RFQ, and LINAC), and cavity tuners as depicted in Figure 1.

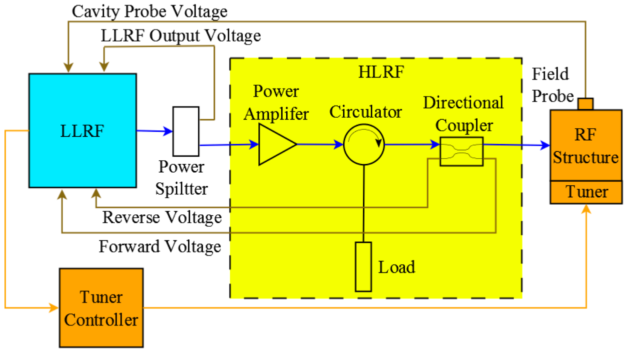

Figure 1: EBIS RF system.

The EBIS LLRF system employs the RHIC LLRF platform, utilizing the Update Link [5] to transmit data and synchronization information between hardware. Figure 2 illustrates the EBIS LLRF system.

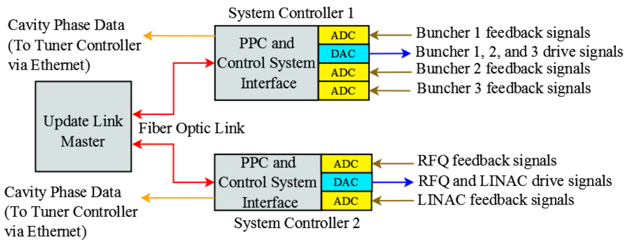

Figure 2: EBIS LLRF system.

Even though the EBIS LLRF system utilizes RHIC's LLRF hardware platform, there are significant differences in software and firmware implementation and capabilities. The EBIS LLRF provides I-Q modulation to the cavity drive at a fixed frequency, cavity arc protection, pulse shape modulation for x-ray suppression, cavity phase detection, and phase difference calculation delivery to tuner controller. Some of these features were implemented as we commissioned the system to resolve unforeseen issues. The EBIS LLRF system is also the first LLRF upgrade platform employing PPM capability [6] for fast species switching specified in the EBIS system specification [1].

COMMISSIONING AND SYSTEM CAPABILITIES

In the initial commissioning system, two basic requirements were implemented: I-Q feedback on cavity drive and cavity resonance control. The simplified I-Q feedback loop block diagram is illustrated in Figure 3. The I-Q feedback loop is implemented via software running on the ADC daughter module's Xilinx Virtex-5 FPGA embedded PowerPC 440 microprocessor, running at 400MHz clock rate. There are always debates about implementing algorithms in software or firmware. In this case, we choose the software route because we expect changes to the code during the commissioning phase Software changes are easy simpler to implement and the performance of the software code is sufficient to meet the requirements. The I-Q reference points are entered through the Parameter Editing Tool (PET) [6]. The software then compares the reference to the sampled I and Q data (I_{live} and Q_{live}) from the phase detector firmware to produce I_{error} and Q_{error}. The errors are integrated and scaled, and then summed to produce the set-points. The integral and proportional gains are also PET parameters that can be changed in real time. The set-points are then sent via the Update Link to the DAC daughter module [7]. The DAC firmware receives the I-Q set-points and converts them to a 16-bit offset binary data to drive the DAC. Output of the DAC drives the high level RF system, which in turn drives the RF cavities.

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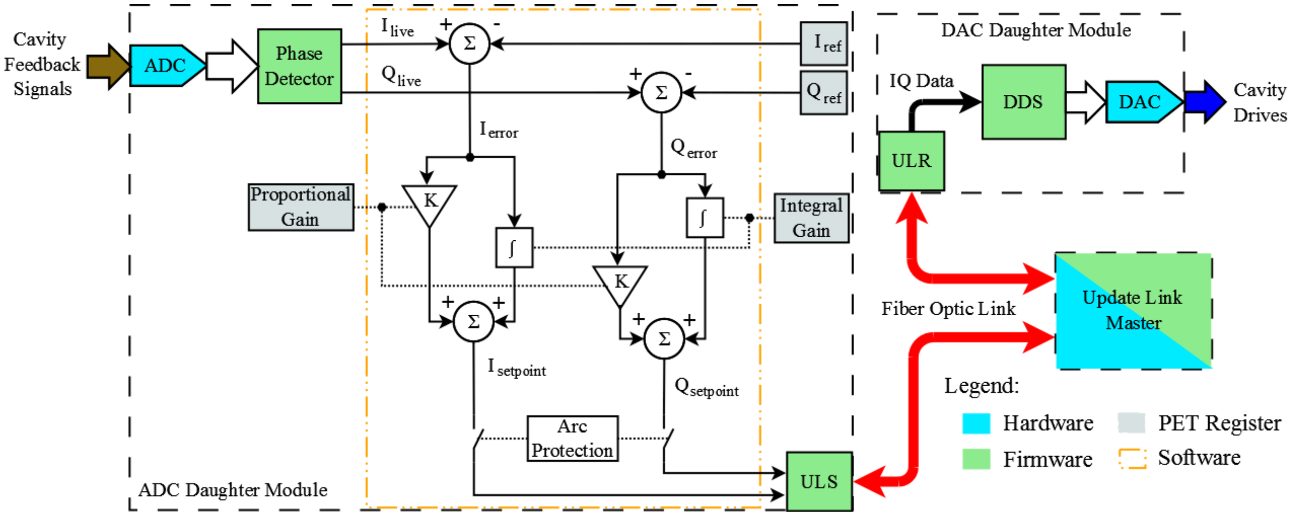

Figure 3: I-Q feedback loop implementation.

Another initial requirement was cavity resonance control. This is accomplished by digitizing the cavity forward and cavity probe voltages. The phase of each signal is obtained from the phase detector firmware. The phases of those two signals are averaged over the RF pulse width. The difference of the averages is sent to the tuner controller via Ethernet. The tuner controller drives the tuner motor to change the cavity resonance frequency. The cavity resonance is kept by the tuner controller maintaining a constant phase difference.

During commissioning, we discovered that the high gradient cavities (RFQ and LINAC cavities) arc at high voltages. We added the arc protection in the software code. Arcing is detected by measuring the amplitudes of the forward and cavity voltages. If there is a significant level of forward voltage, but very low or no cavity voltage, arcing has developed across the cavity. When this condition appears, the I-Q setpoints are set to zero, which results in no RF output, until the next RF pulse cycle.

Another feature added during commissioning was the cavity conditioning scheme. At certain voltages, the RF cavities experience the multipactor effect [8]. To minimize the effect, a cavity conditioning scheme was developed. During cavity conditioning, the voltage of the cavity is increases in 1% steps starting from zero, each step takes one minute until 100% amplitude is reached. Then the process starts over again. Over time, the conditioning scheme minimized the multipactor effect on the susceptible cavities.

The high gradient cavities (RFQ and LINAC) emit levels of x-rays too high for safety requirement [9]. An x-ray suppression scheme was deployed using pulse shape modulation. During an RF pulse, the cavities are brought up to a low voltage to avoid high x-ray emission. Voltage is increased to the desired level during the expected beam arrival time, and then the voltage is dropped back down after the beam left the cavity. The timing of the RF pulse is provided by the embedded V202 delay module [3] on the system controller board. Pulse shape modulation minimizes the time high level x-ray emission occurs.

SYSTEM PERFORMANCE

Figure 4 shows the LINAC RF pulse with and without I-Q loop on with the same amplitude settings. The black trace shows the cavity voltage, red shows the forward voltage, and blue shows the reverse voltage. X-axis is time in microsecond, and y-axis is the digitized amplitude in arbitrary units.

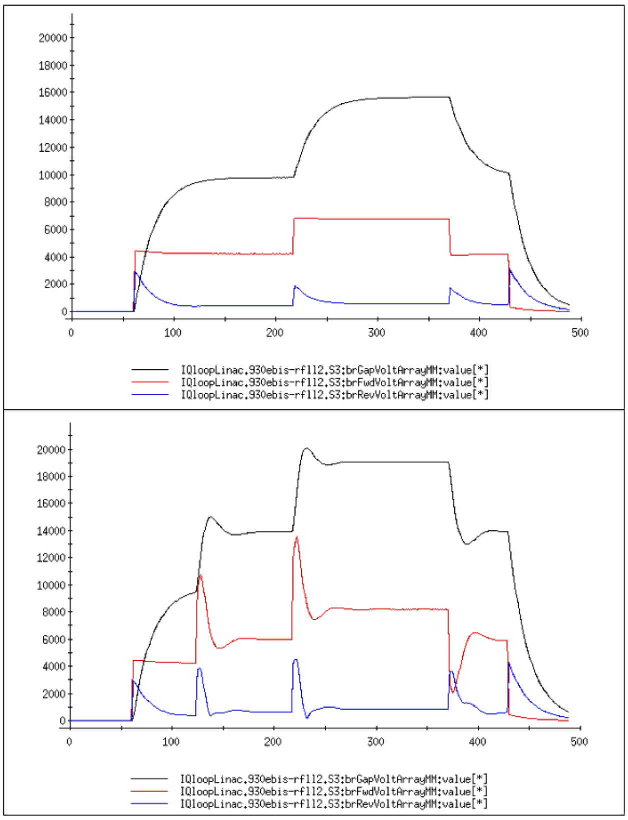

Figure 4: LINAC RF pulse.

The top figure of Figure 4 shows the open-loop RF pulse. The drive is derived from I-Q references from PET only. Without the I-Q loop, the voltage did not reach the set level, and takes a longer time to fill the cavity. The bottom figure shows the pulse with I-Q loop on. The forward voltage is increased to compensate for the cavity fill time, and the desired voltage levels are reached much faster. The I-Q loop response can be adjusted by the proportional and integral gain via PET. It is optimized for fast response while having minimal overshoot. Another feature Figure 4 shows is the x-ray suppression by pulse shape modulation mentioned in the previous section.

The Buncher cavities are more susceptible to the multipactor effect compared to RFQ and LINAC cavities. Figure 5 shows the Buncher 2 cavity voltage amplitude during cavity conditioning. Cavity conditioning usually runs continuously over many days.

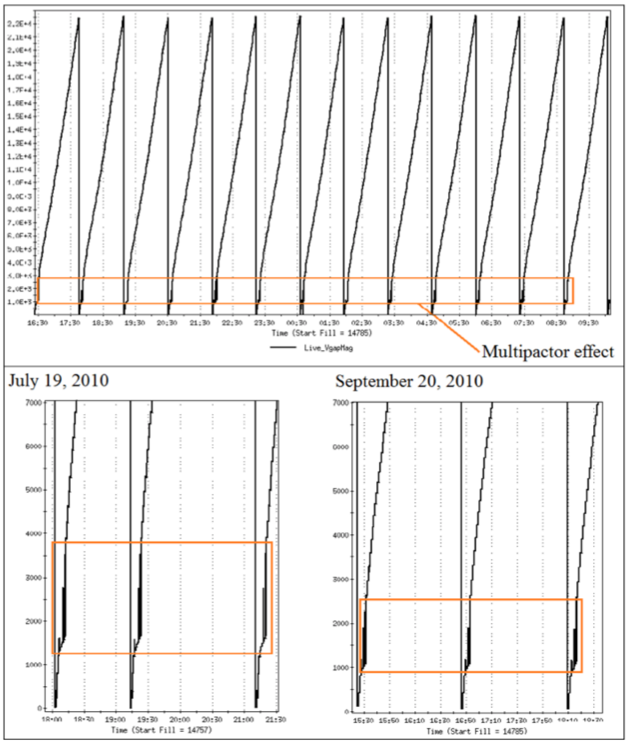

Figure 5: Buncher 2 cavity conditioning.

The top figure in Figure 5 shows the step increase of the cavity voltage. The orange box highlights the multipactor effect. Bottom left and bottom right figures in Figure 5 zoom in to the multipactor effect on July 19th, 2010 and on September 20th, 2010, respectively. The multipactor effect decreased by about 1/3 over this period from running the cavity conditioning scheme.

The cavity resonance control scheme maintains the phase difference between forward and cavity voltages at resonance over slow frequency change introduced by temperature drifts. Figure 6 shows a test of the cavity resonance control scheme of the Buncher 2 cavity. The black trace shows the phase difference. X-axis is time, y-axis is phase in arbitrary units. A one-degree phase difference was introduced to the negative and positive direction. The tuner controller was able to adjust the cavity phase to maintain the original phase difference. The change in phase difference is expected to be slow thermal drift as the cavities warm up or when ambient temperature changes. This test shows that the cavity resonance control loop is able to compensate changes that are much faster.

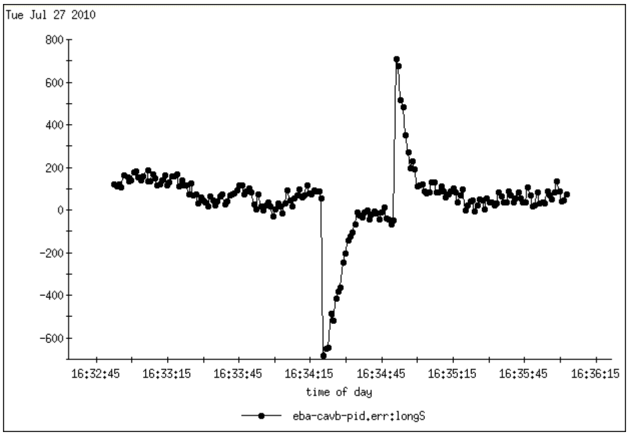

Figure 6: Buncher 2 phase difference between forward and cavity voltages.

CONCLUSION

As the first application outside of RHIC, the EBIS LLRF system shows how flexible the LLRF upgrade platform is. By utilizing the same hardware architecture and implementing system-specific requirements in software and firmware, development time and cost are greatly reduced.

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