FEEDBACK CONFIGURATION TOOLS FOR LHC LOW LEVEL RF SYSTEM *

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Abstract

The LHC Low Level RF System (LLRF) is a complex multi-VME crate system which is used to regulate the superconductive cavity gap voltage as well as to lower the impedance as seen by the beam through low latency feedback. This system contains multiple loops with several parameters to be set before the loops can be closed. In this paper, we present a suite of MATLAB based tools developed to perform the preliminary alignment of the RF stations and the beginnings of a closed loop model based alignment routine. We briefly introduce the RF system and in particular the base band (time domain noise based) network analyzer system built into the LHC LLRF. The main focus of this paper is the methodology of the algorithms used by the routines within the context of the overall system. Measured results are presented that validate the technique. Because the RF systems are located in a cavern 120 m underground in a location which is relatively un-accessible without beam and completely un-accessible with beam present or magnets are energized, these remotely operated tools are a necessity for the CERN LLRF team to maintain and tune their LLRF systems in a similar fashion as to what was done very successfully in PEP-II at SLAC.

INTRODUCTION

The LHC LLRF shares many design elements with the PEP-II LLRF system. In particular the designers of the system included a base band network analyzer similar, yet different from, the one included in PEP II. To keep the loop delay short, thereby maximizing the feedback gain and minimizing the effective cavity impedance, the VME crates implementing the Cavity Controllers are located in a Faraday Cage in the UX45 underground cavern, at 40 m distance from the accelerator tunnel. During LHC commissioning in Summer 2008, the original technique for setting-up the LLRF was executed by two “experts”, in the cavern using a network analyzer. The first benefit of this new technique is the capability to do it remotely. The second one is that it could now be done by several less qualified persons in the RF or Operation groups. After the incident during the 2008 LHC start-up more stringent requirements have been put on access to the LLRF Faraday Cage and as a consequence the importance of these tools has grown significantly.

The PEP-II technique is well documented [1]. Therefore, we will only present a brief overview of the technique. We will discuss some of the key architectural differences between the LHC and PEP-II systems followed by a discussion of the application to the LHC. A brief description of the toolset will be presented. Future directions and follow on work will also be discussed.

TECHNICAL OVERVIEW

Measuring feedback systems in closed or open loop always involves the application of a stimulus and a measurement of a response. Using conventional techniques, involving a network analyzer, it is usually impractical to measure the open loop response of a feedback system except during initial alignment. In the most basic form, we are doing nothing more than measuring a feedback system in closed loop and then using some math to “open loop” the system.

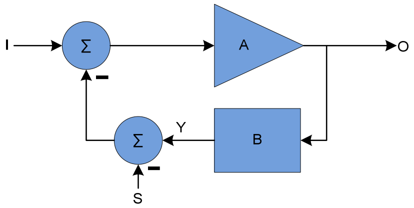

Figure 1: Simplified Feedback Model.

Figure 1. shows a simplified block diagram to illustrate the technique. Solving for Y we get:

$$Y = \frac{AB}{1+AB} I + \frac{AB}{1+AB} S$$

Using this equation and holding I constant (or set to 0) while dynamically changing S, gives a very convenient way to measure the “closed” loop with a very minor perturbation to the closed loop. We use a noise file playback technique and a transfer function estimate to produce a measured transfer function: $H_{meas}(\omega)$. With the measured transfer function in hand, to determine the parameters of the RF station, a linearized model of the system is numerically fit to the measured closed loop transfer function $H_{meas}(\omega)$. Using a gradient descent optimization algorithm, the estimated function $H_{model}(\omega)$ is determined, with a weighted least squares metric. By computing the magnitude of the difference of the two transfer functions, the transfer function phase information is included. Once the closed loop function is fit, we can then open loop the system using the model by simply solving for AB in the above equation.

Besides measuring the closed loop response we measure several open loop responses as part of the overall suite of tools.

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ARCHITECTURE

The actual LHC LLRF architecture [2] is quite a bit more complicated than the simplistic plot shown in figure 1. A more complex (but simplified) block diagram is shown in figure 2 to illustrate several aspects of the tools and to give an overall impression of the complexity of the system. Like PEP-II the LHC LLRF is a Cartesian feedback system [3]. The RF accelerating voltage is demodulated to baseband In phase and Quadrature phase signals (IQ signals). These IQ signals are processed and then re-modulated back on to an RF carrier which is fed via a klystron back into the superconductive accelerating cavity.

The core of the feedback systems is contained within 5 VME modules contained within 2 separate VME crates. The core feedback modules are: Analog Demodulator, Set Point, RF Feedback, RF Modulator, Switch and Limit.

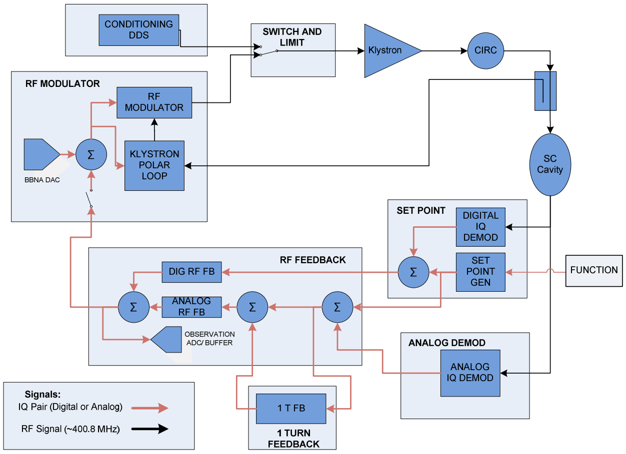

Figure 2: Simplified LHC LLRF Block Diagram.

The system contains several other modules while important for overall system operation, are either not directly in the signal path or implemented yet [4].

A unique feature of the LHC LLRF is the inclusion of a both a low frequency digital feedback path and a higher frequency analog path. The digital path serves as the DC and low bandwidth integrator for the feedback system. These two paths must be phase aligned, during initial station alignment. This phase alignment is the first of the major tools we have developed. Before closing the loop in the feedback system it is important to ensure that the overall loop phase and gain margins are set appropriately to ensure system stability. The second major tool performs this task. Finally, once the loop is closed, a closed loop response must be measured to ensure that the system is stable and well behaved.

All these measurements use a baseband network analyzer (BBNA). At the basic level, the BBNA is nothing more than a high speed DAC used for stimulus and a high speed ADC for measurement. The LHC LLRF design team at CERN chose to include several stimulus points and several response points around the loop. In our final implementation, there was only one stimulus and one response point needed for the bulk of the measurements. For all open and closed loop measurements, we use the stimulus DAC in the modulator module and the response ADC on the output of the RF feedback module. By using these two points we can measure nearly all of the open loop response with only a very small base band cable between the RF Feedback and RF modulator not measured.

The DAC and ADC both operate at a sample rate of 40 MHz. The ADC continually writes data into a circular buffer of size 256 kwords whereas the DAC has a total sample space of 4096 Words. To allow for differing bandwidth measurements, the LHC LLRF designers allowed for both a variable playback rate in the DAC, using a CIC interpolation filter and a variable ADC data decimation to be used if the length of the playback record exceeds the recording length. Although this complicates matters in the MATLAB tool programming, it enables a powerful and flexible control over measurement bandwidths.

For our tools we use the same noise excitation method that was used in the PEP-II LLRF system. A known noise file is played into both the I and Q playback buffers. In the mean time, the circular record buffer is recording the response of the system to the noise file. At the end of playback, a trigger is sent from the BBNA module to all other modules to freeze the record buffers of choice. At this point, the MATLAB scripts are used to calculate and fit the transfer functions and finally suggest corrections to the hardware configuration.

MEASUREMENT TOOLS

To date, there are four main alignment routines. The first three listed below are open loop measurements, with the last routine being a closed loop measurement. We will discuss each routine briefly below:

- Nulling
- Align Analog/Digital Phase (Identify Notch)
- Align Open Loop
- Align Closed Loop

Nulling

The nulling routine is used to null various analog offsets found within the various modules. This routine serves to null any leftover and overall system offsets once all modules are combined into the final system. The routine first nulls the RF feedback ADC's and then uses those ADC's to null the modulator offsets. Finally, a carrier is set in the modulator which is then nulled by setting an appropriate set point in the set point modue. This carrier signal is modulated in the following routines as the stimulus for the BBNA measurements.

Analog/Digital Phase Align

The next step in the initial alignment is to align the digital and analog feedback paths in phase. Leaving the setup as in the previous test routine, we now set a carrier and play back a noise file as a modulation on the carrier.

After running through a transfer function estimate routine and then plotting the resultant function on a magnitude plot we get a result as shown in Figure 3. Both the fit and the measured data are shown on the same plot. By fitting to the measured data, we can very accurately calculate required adjustments to the cavity phase angle adjustment in the set point module.

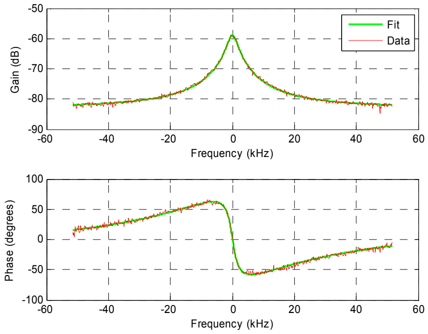

Figure 3: Magnitude and phase response of analog/digital paths.

Open Loop Adjustment

The above two steps should be done only once: At commissioning (or when replacing a faulty LLRF module). From here on however, we present adjustment tools that will be used when changing the parameters of the RF chain (coupler positions, klystron current, klystron power – saturation effect, cavity detuning).

In this step we measure the entire loop including the klystron, circulator and cavity. From this measurement, we can set the overall loop phase and gain so that when the loop is closed, it will be very nearly ideally aligned. To minimize the effect of klystron power supply ripple, we converged upon a scheme where we temporarily disable the digital feedback (and its large gain), such that the large ripple from the klystron power supply is filtered out. The steps in this procedure are nearly identical to those in the Analog/Digital phase alignment procedure. As can be seen in Figure 4, an initial measurement is taken and then the overall loop phase is adjusted until the overall response is at 180 degrees.

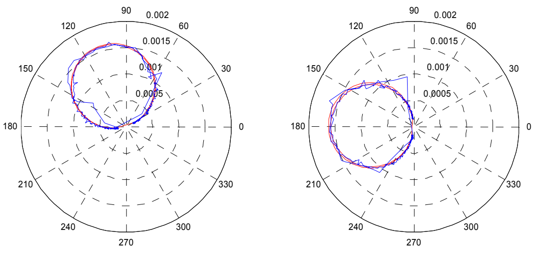

Figure 4: Initial and rotated loop phase.

Closed Loop Measurement

The closed loop measurement routine, first lowers the gain in the analog and digital feedback, referring to figure 2, and then close the loop using the loop switch in the RF modulator module. We then do the exact same measurement as before in the previous two routines.

This routine will be used routinely and in fact will be the only routine which could potentially be run with beam. At first it will not be run with beam, but follow on work may be done to enable the LHC LLRF team to make parasitic measurements without perturbing the beam. Figure 5 shows some preliminary results from the closed loop response and fitting.

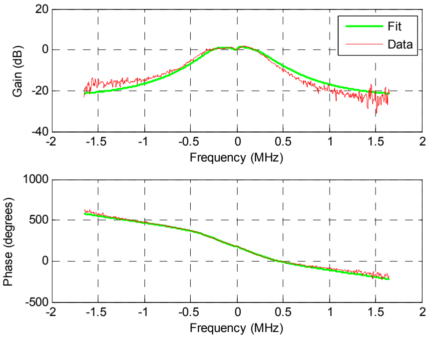

Figure 5: Closed loop measurement and fit.

CONCLUSIONS AND FUTURE WORK

We have presented an overview of the tools and progress to date on the remote alignment tools for the LHC LLRF. There is more work to be done. The Klystron used in this system has a gain bump approximately 4 MHz away from the center frequency. The RF Feedback modules contain a variable frequency resonant notch which is used to mitigate this gain bump. We are currently working on a routine to automate the alignment of that notch. In addition, more work needs to be done on the closed loop routine so that we can properly suggest changes to the loop gain and phase. Finally, the LHC LLRF polar loop around the Klystron needs initial alignment and closed loop verification. The polar loop routine will also be remotely configurable.

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