LLRF HARDWARE TESTBENCH*

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Abstract

With continual advances and the development of new technologies, such as superconducting cavities and digital signal processing, particle accelerators have become more powerful and complex. New accelerator designs have more demanding stability requirements for the cavity RF fields, up to 0.01% in amplitude and 0.01˚ in phase for hundreds of cavities in Continuous Wave (CW) or pulsed operation [1]. Compensating for disturbances from mechanical resonances, microphonics, natural couplings and unwanted channel crosstalk is a challenge for the Low Level Radio Frequency (LLRF) control systems. For the upgrade to the Linac Coherent Light Source (LCLS-II) at SLAC, a high performance LLRF control system is being designed and developed to drive the Solid State Amplifiers (SSA) and control the cavity fields within specifications. The different components of the LLRF hardware have been designed, constructed and tested separately during the development process. Here, we describe a test environment, still under development, for integration, characterization and qualification of the LLRF system with all the LLRF hardware integrated in a single prototype rack. This test environment is managed by a python script wrap via Ethernet from a PC which aims, in the long term, to facilitate and automate the test procedure for all the LLRF racks to be installed at the LCLS-II. To simulate a narrow bandwidth, high Q cavity in the absence of a superconducting cavity and a cryomodule, a cavity emulator scheme was developed and used to test the LLRF system.

INTRODUCTION

Low Level RF (LLRF) systems aim to control the magnitude and phase of RF fields for cavities in a particle accelerator (Figure 1). Stability requirements could be as tight as 0.01% in magnitude and 0.01˚ in phase for time periods shorter than 1 second. In order to achieve these requirements, the design must compensate for a variety of disturbances such as mechanical resonance, microphonics [2], natural coupling and unwanted crosstalk. Microphonic detuning, mechanical resonances and coupling depend, for superconducting cavities, on the cryomodule structure and the accelerator environment, where nanometers of mechanical deformation can induce detuning on the order of tens of Hz [3]. Since the cavity bandwidth is also in the order of tens of Hz, the accelerator is very sensitive to the perturbations mentioned above. To avoid adding any additional noise, it is critical to design a low-noise signal

chain for the cavity field. For the LCLS-II LLRF system, this has been achieved by processing the cavity signals in a separate temperature controlled chassis, the Precision Receiver Chassis (PRC), while the forward and reflected signals are processed in the RF Station (RFS), a chassis that also generates the RF drive signal [4]. A complete and integrated characterization of all the LLRF hardware is needed to verify the correct operation of the system is within specifications. In this paper we describe a test environment, still under development, which provides measurements of the field amplitude for the cavity, and forward and reflected signals under different parameters.

Since a large particle accelerator is composed of hundreds of cavities, large-scale equipment tests procedures should be designed in an automated way to allow fast, reliable and simple testing. In our setup, a python script acts as a wrap to control both the PRC and RFS via Ethernet, taking measurements automatically and allowing statistical analysis.
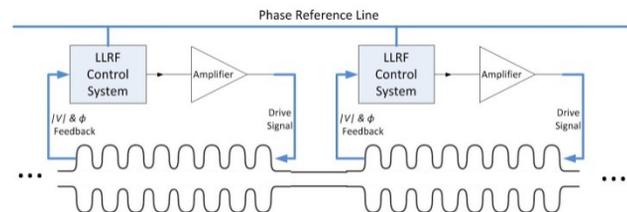

Figure 1: LLRF General Layout.

TEST ENVIRONMENT

The test environment (Figure 2) was developed to characterize, in an integrated way and without a real cavity and cryomodule, the hardware designed for the LLRF system. The test environment consists on the LLRF rack, which contains the RFS and PRC chassis, and a cavity emulator. The PRC chassis contains a down converter, a digitizer board and an FPGA board. The RFS contains the same components and an in addition an up converter. The 1.3 GHz signal from the RFS used to drive the cavity is down converted with a 1.25 GHz Local Oscillator (LO) to obtain 50 MHz, the frequency at which the emulator resonates. Forward and reflected signals are taken with a decoupler and up converted with the 1.25 GHz LO and then measured by the RFS. The cavity signal is also up converted with the 1.25 GHz LO and then measured by the PRC. Forward and reflected signals are processed in a separate chassis from the cavity signals to avoid crosstalk. The PRC is located at the bottom half of the LLRF rack. This allows us to control its temperature to $\pm$ 2˚C. The 1.32 GHz LO is the clock frequency reference for the digitizer board (ADC and DAC) and for the FPGA [3].
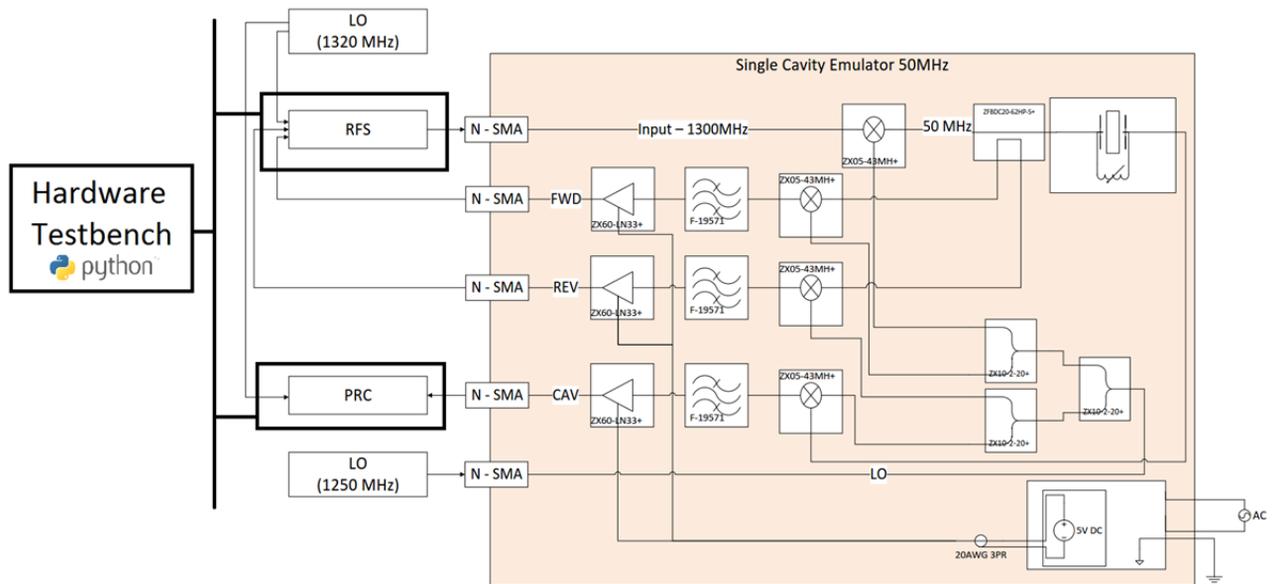
Figure 2: Test environment at SLAC used to characterize the LLRF hardware with a cavity emulator.

TEST SOFTWARE

A script written in Python defines the amplitude and the frequency of the drive signal generated by the RFS to drive the cavity. It also collects data from the loopback, forward and reflected signals acquired by the RFS. The loopback signal is used to monitor the drive signal independent of the RF distribution. Since the RFS and the PRC share the six channel downconverter board design, the eight channel ADC board and an FPGA, the same python script works to collect measurements from the cavity signal going to the PRC. In all measurements shown sets of 1000 measurements of amplitude for a fixed amplitude and frequency of the drive signal are taken.

Figure 3: Gaussian tendency of collected data.

HARDWARE CHARACTERIZATION

After taking 1000 measurements of amplitude of the loopback, forward, reflected and cavity signals at a fixed amplitude and frequency of the drive signal, the collected data has a clear Gaussian tendency (Figure 3), as expected, due to the nature of the noise in the measurements determined by the setup itself. The mean value (μ) and the standard deviation (σ) are computed for every dataset. For a drive signal amplitude of 32000 counts, the loopback mean value is 3335.3245. This corresponds to an attenuation of -20 dB, which is the expected level due to the hardware implemented to acquire the signal. The accuracy on the measurements depends on the different equipment used and the test environment.
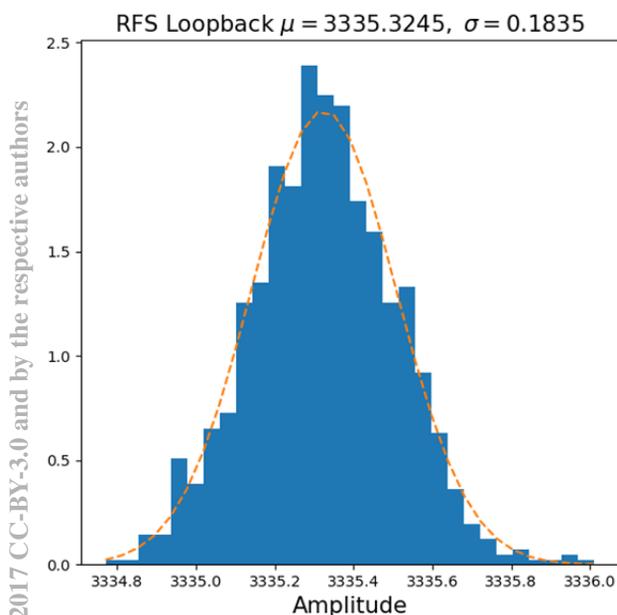
The relationship between the standard deviation and the mean value shows information about the stability of the system. Results in Figure 4 show that the larger the amplitude of the drive signal, the better the stability of the collected data. It is also important to mention that for most of the measurements, the amplitude stability is better than 0.01% for all measurements taken with the amplitude drive set point above 12000 counts of amplitude. 32000 counts correspond to the chassis nominal full-scale of +10dBm. These measurements strongly depend on the quality of the 1.25 GHz LO, since it is used to down convert the 1.3 GHz signal to 50 MHz, and any variation on the centre frequency affect the output power of the cavity emulator. Also, the measurements are the result of the capabilities of the test bench and do not represent the performance of the RFS or PRC.

Measurements of the PRC cavity signal were collected at 2 different positions: at the bottom half of the rack, close to the cooling system, and at the top half of the rack, far from the cooling system. The cooling system controls the temperature to ± 2°C.
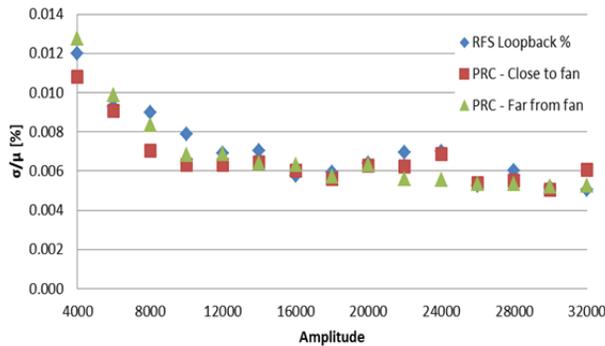
Figure 4: Amplitude stability.

Every set of 1000 measurements takes about 3 minutes. Drifts presented as a slope in the data, as shown in Figure 5, affect the absolute stability of the measurements. These drifts are assumed to be caused by an external bias and should be removed by re-calibrating methods and will be done so in the future when the source of error is found.
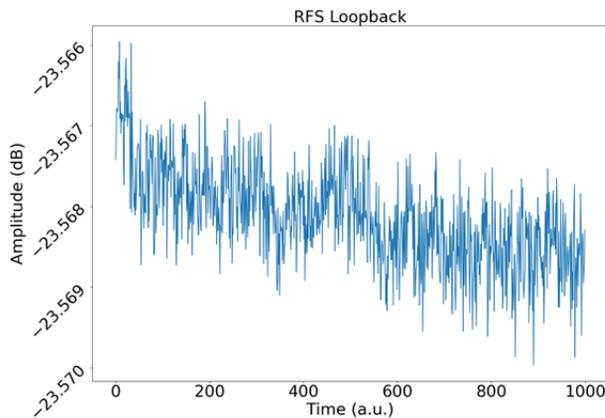

Figure 5: Amplitude Drift.

CONCLUSIONS

A hardware bench test for the LLRF system composed of an RFS, PRC and a cavity emulator has been developed to characterize LLRF hardware at SLAC. The goal was to provide a rapid and automated method of performing the test measurements of the tens of LLRF racks that will be used to monitor and provide drive signals for the thousands of superconducting cavities of the LCLS-II. A Python script has been developed to collect and plot the data in an automated way as well as to perform the requisite statistical analysis. Results obtained show acceptable behaviour, but there is still room for improvement. Our next steps include phase measurements taken to perform phase stability analysis; however, a prototype of the phase reference line is still under development [5]. Also, the SSA should be included in the testing procedure as well as an EPICS interface that will allow visualization of data acquisition in real time. Python and EPICS communication will be a crucial factor.

Automated and reliable testing of hardware and software is a factor of high importance when massive production of boards and chassis starts for a particle accelerator of hundreds of cavities. Introducing a novel approach for testing the equipment is essential at accelerators like the LCLS-II at SLAC. With future improvements, we are expecting to test tens of racks, with hundreds of chassis and boards. The results presented show the capability of the test procedure and do not represent the performance of the RFS or PRC.

ACKNOWLEDGEMENTS

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