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LOW-LEVEL RF SYSTEM DEVELOPMENT FOR A C-BAND LINAC

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Abstract

RadiaSoft and RadiaBeam are partnering on the development of a low level RF control system to support a 100 MeV C-Band LINAC. Our system utilizes a Keysight data acquisition system and arbitrary waveform generator to drive the LINAC. The controllers are fully integrated with EPICS and are actively being commissioned. In this presentation we will provide an overview of the design architecture, discuss details of the epics integration, and show initial results controlling a photoinjector.

INTRODUCTION

The Low-Level Radio Frequency (LLRF) control system is primarily responsible for delivering RF to amplifiers, receiving and processing signals for the various RF diagnostics, and control of the RF cavities to include phase, amplitude, and frequency. When building a LLRF system there are a number of design considerations that lead to the choice of frequency parameters, digital vs analog, and how to modulate the RF signals. One of the most common architectures utilizes an intermediate frequency that is used for digitization and an analog system to perform up and down conversion [1]. However, base-band modulation has also been used, for example the Swiss FEL utilized such an architecture [2]. Additionally, modern electronics are making systems that perform direct digital down-conversion more popular [3]. For C-Band there are limited commercial options for direct digital sampling that are also cost effective for a modest scale system. This is largely due to the development time required and operating in unusual modes such as the first Nyquist band. Moreover, the technical challenges associated with base-band modulation and noise mitigation makes a digital system operating at an intermediate frequency more attractive. As such we chose to build a COTS system based on digitization at a reasonable intermediate frequency with cost effective solutions. Figure1 shows a functional block diagram of our COTS LLRF system. Here we highlight the notable interconnections and signals. For this system, we have a common local oscillator that is distributed to all of the analog electronics. The digital system generates a clean reference signal that is re-distributed to the LLRF system as a phase reference and also distributed to the timing system and the laser system for phase locking. The parameters for the LLRF system are given in Table 1.

This paper provides an overview of the digital and analog components of the LLRF system as well as measurement of losses through the downconverter and amplitude stability measurements. We also describe the EPICS integration at a high level and provide a brief overview of the high level applications used to control the accelerator.

Table 1: Parameters for the LLRF System

Parameter	Value
RF	5712 MHz
IF	100 MHz
LO	5812 MHz
Laser	476 MHz
Sample Rate	500 MS/s
ADC	14 bit
DAC	16 bit

DIGITAL SYSTEM DESIGN

The digital system is comprised of a an M3102A PXIe Digitizer from Keysight and an M3201A PXIe Arbitrary Waveform Generator also from Keysight. Our AWG resolution is 16 bit at a 500 MS/s sample rate. The digitizer resolution is 14 bit at a 500 MS/s sample rate.

The choice of intermediate frequency is largely determined by the available digital components and the constraints on RF filtering, This typically is in the 10 – 100 MHz range. Our initial choice of the intermediate frequency is 100 MHz. This is to allow for good isolation between IF signals, RF signals, and baseband signals. When converting from RF to IF, the RF signal at 5712 MHz is mixed with the LO at 5810 MHz. This will generate a 100 MHz signal and a 11524 MHz signal. The 11.5 GHz signal will be filtered out using analog components leaving the 100 MHz signal. The IF signals will be digitized at a rate of 500 MS/s which is readily available with modern digitizers. The choice of a digital system that is 2.5x Nyquist will provide higher signal quality while maintaining a reasonable cost. The digitizers have a bandwidth of up to 200 MHz and we will show results of our system with an IF of up to 175 MHz. To extract the RF waveforms the 100 MHz signal is mixed digitally with another 100 MHz signal giving a baseband waveform and a 200 MHz signal. In order to resolve the cavity dynamics, we need a minimum of 20 MHz bandwidth at baseband. Having 200 MHz of space between the baseband signal and the secondary signal generated by the IF downmixing relaxes the constraints on the filter design and reduces the need for high order filters that cause ringing and other unwanted effects.

The arbitrary waveform generator has built in I/Q modulation for phase coherent signal generation. It can generate sinusoidal signals with envelope and phase modulation all synchronized to an internal reference clock. The DACs are 16 bit which provides a high level of precision for the RF

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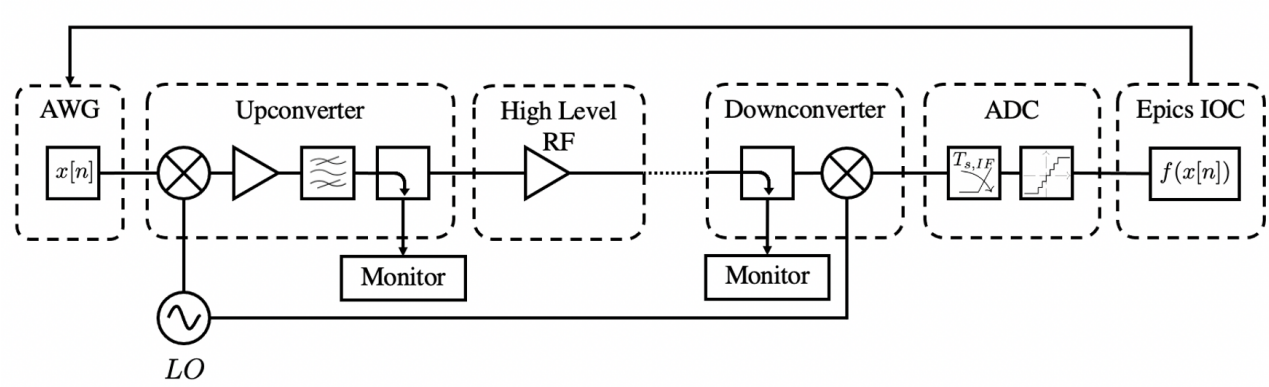

Figure 1: Schematic of the LLRF system. The dashed line in the middle notes a break where the RF cavities and directional couplers are.

drive signals. The digitizers are each four-channel analog to digital converters (ADCs) that sample based on the same fixed clock as the DACs. The ADCs operate at 500 MS/s and have 14 bit resolution. This was chosen to allow for precise measurement of the RF amplitude and phase at various locations in the RF network. 500 MS/s is a compromise on cost with sample frequency. Higher frequency ADCs and DACs would provide higher performance with regard to control and noise reduction. We performed tests of the 500 MS/s system to ensure the reduced sampling capacity would still provide the desired phase and amplitude stability.

ANALOG SYSTEM DESIGN

The analog system is comprised of three major components, the downconverter, the upconverter, and the local oscillator distribution. For this system we chose a connecterized solution to avoid board design and layout engineering. The downconverter chassis includes RF monitor ports to the front panel to allow for diagnosing the system.

The upconverter chassis is very similar to the downconverter chassis by design. Aside from the filters and amplifiers, the components are identical. This enables the efficient construction of each system. We also include monitors for the RF signals to enable efficient diagnosis of issues with the generated RF signals before they go to the amplifier chain. The LO distribution is handled by amplifying the LO source and then splitting it 8 ways providing signal to the various analog systems. We built a single LO distribution chassis that can generate 8 LO signals. Testing of the analog system includes both the component level testing and the system level testing.

As part of the downconverter testing we verified the conversion loss between the back-panel and the front panel for the downconverters. The mixers are specified to have around 10 dB of conversion loss but this varies slightly from component to component. We measured the conversion loss by driving the back panel with a 5712 MHz signal and measuring the front panel signal with a spectrum analyzer. Note that we also measured the front panel with a power meter but due to some signal leakage that is filtered out in the digital

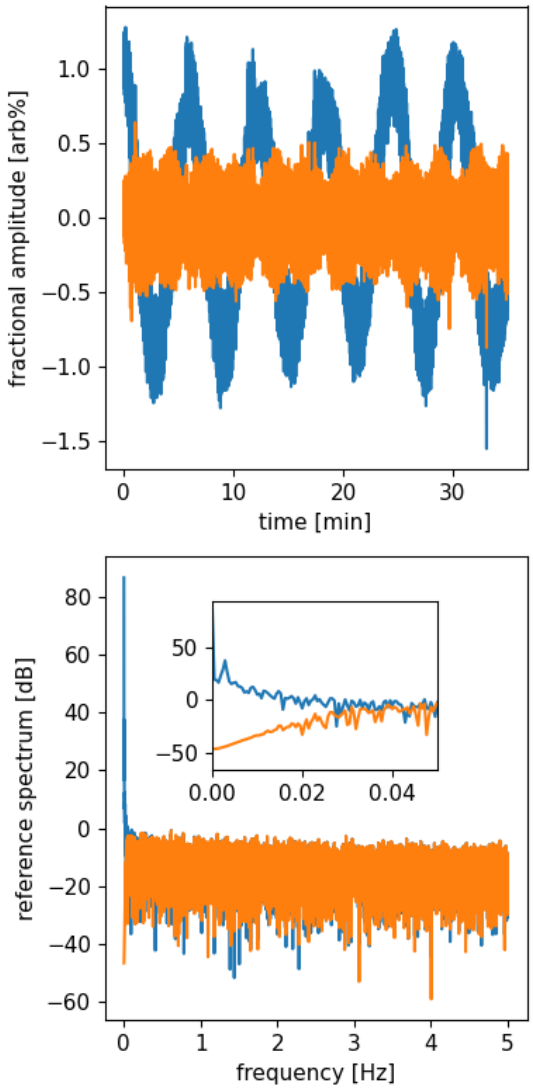

Figure 2: Comparison of conversion loss measurements for the downconverter using a power meter(dashed lines) and a spectrum analyzer (solid lines). The slope and offset for each channel are shown in the respective captions.

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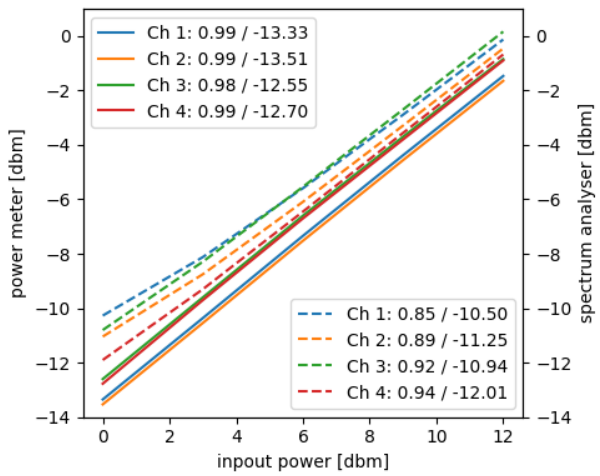

Figure 3: Fractional variation in the reference signal measured by the keysight ADC before and after filtering to remove thermal fluctuations. Peak to peak noise is less than 0.5%. Bottom shows the frequency spectra along with an inset plot showing the low frequency components being removed by the filter.

system we see an amplitude dependence on the conversion loss. Figure 2 shows the output power as a function of input power for four channels on one of the downconverters. When measured with the spectrum analyzer we have very good linearity across all channels.

STABILITY MEASUREMENTS

In order to evaluate the stability of the system without the klystron in the loop we analyzed the reference signal data measured with the Keysight system. The reference signal is generated by the arbitrary waveform generator, converted to 5712 MHz with the analog system, then split for synchronization with the laser and downcovnverted to 100 MHz before being digitized again for use in phase synchronization of the system. This measurement is an in the loop diagnostic on the amplitude noise generated by the digital and analog LLRF systems. Figure 3 shows the fractional change in amplitude over 35 minutes as a percentage of the drive amplitude. Blue is an unprocessed signal and orange is the same signal with a high pass filter applied to remove the long time oscillations. These oscillations correlate with the AC unit cycle on the LLRF rack. The bottom plot shows the frequency spectra of the signals both before and after filtering.

Here the inset plot shows a zoomed in version where the low frequency signal can be seen as a small uptick in the power spectra. The peak-to-peak amplitude noise with this modulation filtered out is ±0.5%. Well within the specification for our system.

EPICS INTEGRATION

Integration with EPICS includes high level applications for operation of the LLRF system. Windows drivers were required for the Keysight ADCs and DACs. This included

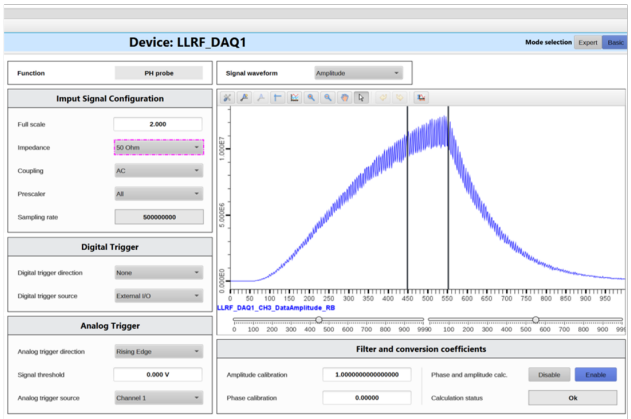

Figure 4: Screenshot of expert display for the LLRF system.

significant debugging to ensure proper timing for accurate signal processing and data logging. Early testing showed a possible memory leak at high repetition rates causing the IOC to freeze. This was resolved and the EPICS IOC has demonstrated robustness over long timescales at higher repetition rates. The EPICS IOC runs on the Keysight controller computer located in the PXIe chassis.

High level applications were built to provide an overview of the LLRF signals through waveforms and scalar readbacks. Additionally expert displays provide detailed information about the ADCs and DACs. Figure 4 shows a screenshot of the EPICS display for one of the probe readbacks. Within the EPICS IOC averaged signals are produced with a variable window settable by the user.

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