C-BAND LOW LEVEL RF SYSTEM USING COTS COMPONENTS

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Abstract

Low Level RF systems have historically fallen into two categories. Custom systems developed at national laboratories or industrial systems using custom hardware specifically designed for LLRF. Recently however advances in RF technology accompanied by demand from applications like quantum computing have led to commercially available systems that are viable for building a modular low-level RF system. Here we present an overview of a Keysight based digital LLRF system. Our system employs analog upconversion and downconversion with an intermediate frequency of 100MHz. We discuss our phase-reference system and provide initial results on the system performance.

INTRODUCTION AND HIGH LEVEL ARCHITECTURE

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. Figure 1 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.

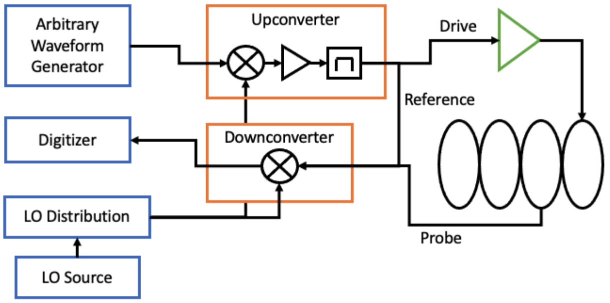


Figure 1: High level schematic of a generic LLRF control system.

In this paper we will provide an overview of our design choices and share some initial results of our phase and amplitude stability, noise levels, and linearity.

DIGITAL SYSTEM

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 11.5GHz 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 200Mhz and we will show results of our system with an IF of up to 175MHz. To extract the RF waveforms the 100 MHz signal is mixed digitally with another 100MHz signal giving a baseband waveform and a 200MHz signal. In order to resolve the cavity dynamics, we need a minimum of 20 MHz bandwidth at baseband. Having 200MHz 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.

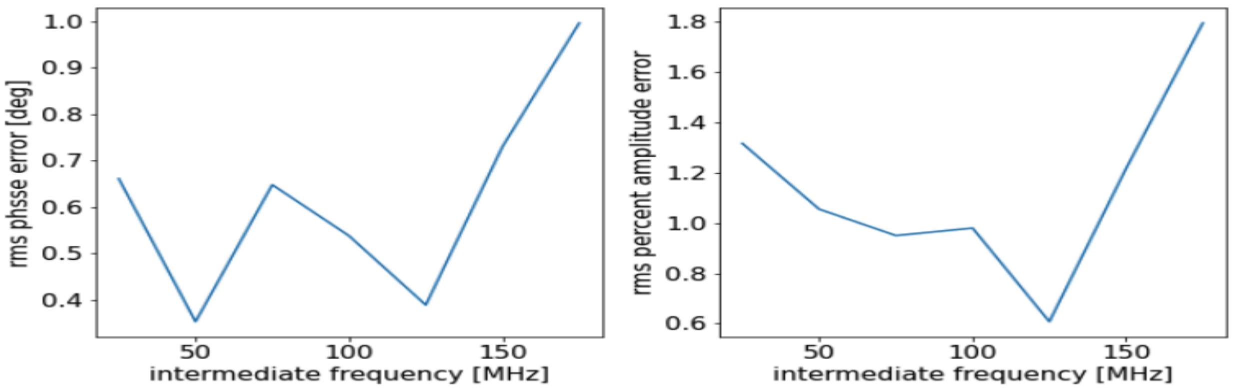


Figure 2: Measurements of phase and amplitude stability as the intermediate frequency is varied.

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 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. Figure 2 shows the amplitude noise and phase noise as we vary the intermediate frequency. Our budget is around 0.5 degrees phase noise and 1% amplitude noise. Thus an intermediate frequency of around 100MHz should be adequate. Note that this measurement includes components used for the upconverter and downconverter system.

The RF control algorithms are implemented run through the digital LLRF system. We have implemented an EPICS driver for both the M3102A digitizer and M3201A AWG. We have EPICS based input-output-controllers that communicate between the main user interfaces and the LLRF computer that lives in the Keysight chassis.

ANALOG SYSTEM

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 downconverter signals are sent directly to the digitizers. Mixers and filters are specified. 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. The mixers are the largst source of nonlinearity in our system. Figure 3 shows the output amplitude of the mixer as a function of the input amplitude for three different LO settings.

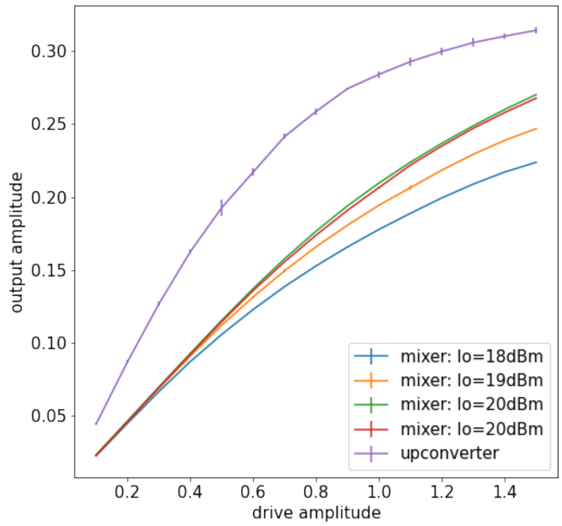


Figure 3: Output of the mixer and upconverter as a function of the drive amplitude for different LO levels.

Here we see a fairly straightforward nonlinear response of the mixers in our range of operation. While this is not ideal, nonlinear calibration curves can be implemented in software to correct for this behavior. We also evaluated the response of the whole system, Figure 4 shows the output

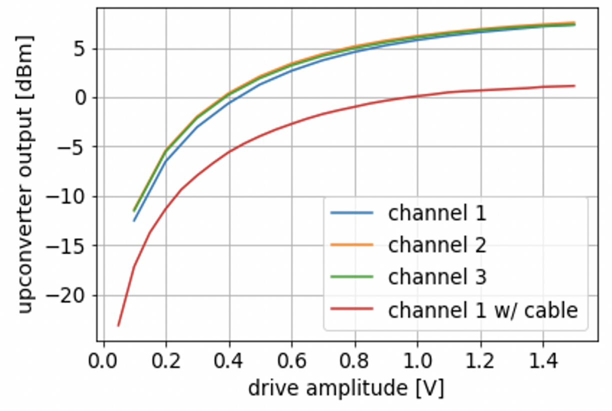


Figure 4: Output of mixer as a function of the drive amplitude for different LO amplitude settings. We also show the output of the upconverter to highlight the increase in noise due to other components.

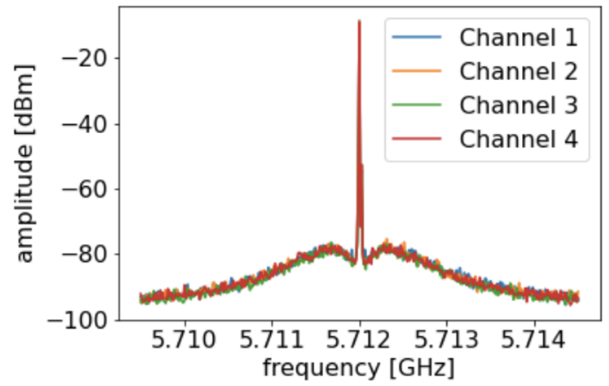


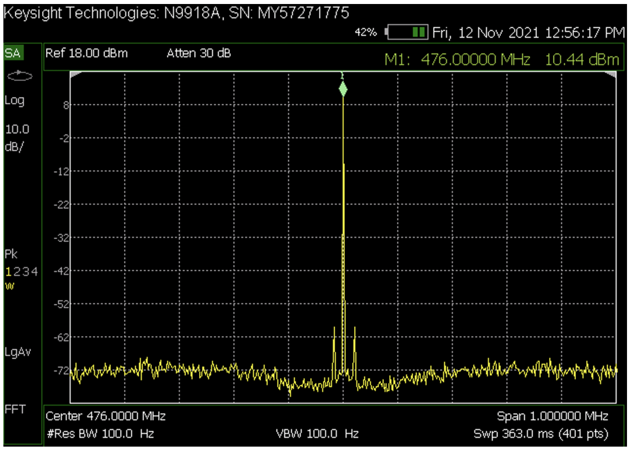
Figure 5: Frequency spectrum measurement of the four channel upconverter

amplitude of the upconverter as a function of drive amplitude for the different channels both with and without the addition of the drive cable. Because cables are so lossy at C-Band we need to build in significant overhead on the output of the upconverter to account for these losses.

We also measured the frequency spectrum of the upconverter to verify a clean signal. Figure 5 shows the frequency spectrum of the upconverter output near the center frequency showing a relatively good noise level.

TIMING AND REFERENCE SYSTEM

The final piece of our system is the timing and reference signal distribution. The reference signal is generated by the AWG and sent to the upconverter. The signal is then sent back to the digital system for digitization as the phase reference and sent to the laser / timing system for synchronization. The signal is divided down to 476MHz and then split with one signal going to the laser and one to another divider that generates a 39.667 MHz signal to be utilized by the timing system. Figure 6 shows the frequency spectrum of the laser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42% Fri, 12 Nov 2021 12:56:17 PM
Ref 18.00 dBm Atten 30 dB M1: 476.00000 MHz 10.44 dBm
Center 476.0000 MHz Span 1.000000 MHz
#Res BW 100.0 Hz VBW 100.0 Hz Swp 363.0 ms (401 pts)

Figure 6: Frequency spectrum of the 476MHz signal that is used for laser synchronization.

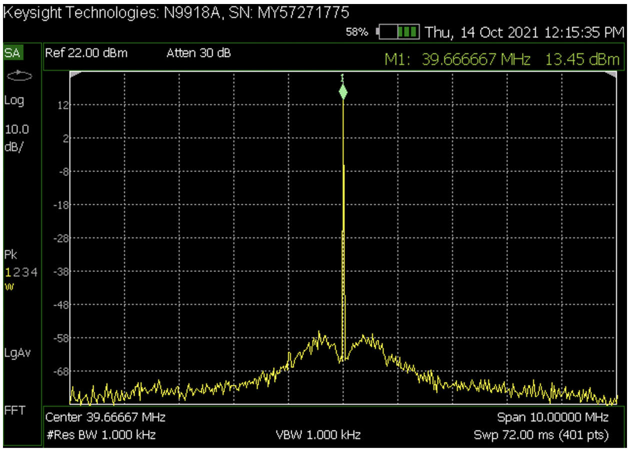
Keysight Technologies: N9918A, SN: MY57271775
58% Thu, 14 Oct 2021 12:15:35 PM
Ref 22.00 dBm Atten 30 dB M1: 39.666667 MHz 13.45 dBm
Center 39.66667 MHz Span 10.00000 MHz
#Res BW 1.000 kHz VBW 1.000 kHz Swp 72.00 ms (401 pts)

Figure 7: Frequency spectrum of the 39.667 MHz signal used for timing synchronization.

signal and Figure 7 shows the frequency spectrum of the timing system.

CONCLUSIONS

We have developed a commercial off the shelf C-Band LLRF system for controlling a compact LINAC. We have performed preliminary componet testing and are in the process of comissioning the system and evaluating long term stability.

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