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COMMISSIONING OF A NEW X-BAND, LOW-NOISE LLRF SYSTEM

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Abstract

To increase beam energy in the CLEAR facility at CERN and study the CLIC accelerating structure prototype in operating conditions, the first X-band test facility at CERN was upgraded in 2020. Both, the acquisition and software systems at X-band test stand 1 (Xbox1) were upgraded to exhibit low phase noise which is relevant to klystron based CLIC and to the use of crab cavities in the beam delivery system. The new LLRF uses down-conversion which necessitates a local oscillator which can be produced by two different methods. The first is a PLL, a commonly used technique which has been previously employed at the other X-band facilities at CERN. The second is a novel application of a single sideband up-convertor. The up-convertor system has demonstrated reduced phase noise when compared with the PLL. The commissioning of the new system began in late 2020 with the conditioning of a 50 MW Klystron. Measurements of the quality of the new LLRF will be shown. These will compare the PLL and up-convertor with particular attention on the quality of the phase measurements.

INTRODUCTION

Since 2010 CERN has been operating several X-band testing facilities capable of producing high power, short pulse length, RF power for testing CLIC prototypes. Starting in 2019, Xbox1 was updated and connected to the CLEAR facility where a CLIC prototype can be used to boost the beam energy using an RF power source rather than the drive beam which is no longer available [1, 2].

The LLRF system for Xbox1 generates phase modulated pulses which can be compressed with a pulse compressor. This is also the working mode of a proposed CLIC low energy machine powered using klystrons rather than a drive beam [3].

In the new LLRF system for XBOX1, we require the ability to measure phase and amplitude of signals by digitally sampling at an intermediate frequency (IF) with high accuracy. Firstly, in any accelerator, this is important to maintain beam quality by controlling the phase of accelerating structures. It is particularly important in CLIC to guarantee the synchronization between crab cavities and preserve luminosity [4]. Indeed, the LLRF system should be able to measure klystron phase jitter and phase drifts in passive components that might vary with temperature and ground motion. In general, the LLRF system should be able to compare phase between any locations where a directional coupler samples forward and reflected power.

Moreover, the X-band test facilities at CERN are designed to condition CLIC prototypes and monitor vacuum breakdowns within. Locating breakdown events assists in analysing the factors that affect them and allows to identify "hot spots". Breakdowns are located by comparing the time at which transmitted power collapses to the time that the reflected power rises [5]. As the CLIC travelling wave cavities operate with a fixed phase advance per cell, the phase of the reflected signal with respect to the forward signal can give the final validation on the cell in which the breakdown occurred. We can also detect a discharge that moves in the structure by accurate measuring the phase. For this application, accurate synchronisation between the 2.99855 GHz RF system of CLEAR and the 11.9942 GHz RF system of XBOX1 is required. Generation of the phase modulated drive signal for the current upgrade has been recently reported [6]. This paper focuses on the generation of the local oscillator (LO) signal needed to down convert signals sampled either side of devices under test to a suitable IF frequency for digital sampling.

XBOX1 UPGRADE

In order to minimise additional phase noise the local oscillator frequency is derived from the 2.99855 GHz RF CLEAR master oscillator by minimal division, multiplication and mixing.

The choice of IF and sampling scheme is determined in part by the availability of digitizers and processing power. NI PIXe-5162 4 channel, 10bit, 800 MS/s digitizer cards are currently used at Xbox1 [7].

The IF was chosen below 200 MHz to allow a range of high precision digitizers to be used. This allows quadrature sampling for sampling rates above 800 MS/s. Quadrature sampling uses far less computing power than asynchronous sampling and with 8 channels to be digitized computing power had become an issue. The IF was chosen as $\frac{1}{16}$ of the CLEAR master oscillator frequency equals 187.409 MHz. In order to down convert to the IF a local oscillator at 11.806 79 GHz must be generated.

PRODUCING A LOW NOISE X-BAND LOCAL OSCILLATOR

Now that the IF frequency has been determined, the local oscillator frequency is also known. The 11.9942 GHz RF will be mixed down to 187.4 MHz using a local oscillator at 11.806 GHz. This frequency must be generated from the 2.998 554 GHz master oscillator. The quality of the local oscillator directly affects the quality of the measurements.

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LO Generation Using a Phase Locked Loop

At Xbox2 and Xbox3 local oscillators have been generated with a PLL. Phase locked loop is a negative feedback loop which uses a phase detector and a voltage controlled oscillator to produce an output frequency with constant phase angle relative to the input signal. They are commonly used to produce a stable high frequency signal from a low frequency input. A frequency divider in the feedback loop is used to set the output frequency, the input frequency will be multiplied by the division ratio to produce a higher frequency output signal [8, 9]. The PLL at Xbox1 is the AFD5355 model which is a wideband PLL that can produce output frequencies from 5 GHz to 13 GHz [10].

LO Generation Using a Single Side-Band Up-Convertor

A single side-band mixing scheme is proposed as an alternative to the PLL which generally exhibits high phase noise. The full up-convertor schematic is shown in Fig. 1.

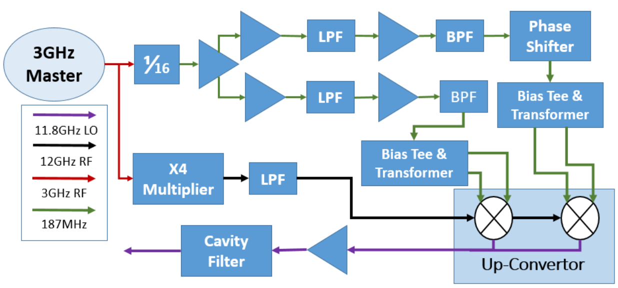

Figure 1: Single Side-band Up-Convertor Schematic.

Mixing the IF generated by division of the master oscillator (MO), with the RF generated by multiplication of the MO, would give the LO frequency plus and minus the RF frequency. Single side-band generation can be achieved using balanced mixers and quadrature (90°) hybrids. The two balanced mixers within the single side-band mixer are driven in quadrature by the IF signals. The LO drive to each mixer is in-phase and the output is combined in quadrature [11]. The chosen up-convertor is the ADRF6780. According to the data-sheet the achievable side-band suppression for this device is 25 dB [10]. Filtering after the up-convertor can further improve the suppression.

The up-convertor requires four baseband IF input signals which must be amplitude matched and correctly phased (I, -I, Q and -Q).The RF input to the up-convertor at 11.9942 GHz was generated from the 2.9985 GHz MO using a Marki AQA1933K active multiplier. This multiplier suppresses 2nd and 3rd harmonics by 10 dB. The output was then filtered using using a Marki FB1215 low-pass pass filter.

Custom Cavity Filter

The LO from the up-converter is at 11.806 GHz but there will be significant side bands at 11.9942 GHz and 12.182 GHz as well as smaller side-bands near 9 GHz and 15 GHz. A filter centred on 11.806 GHz and 45 dB of suppression at an offset of 200 MHz is not commercially available hence a custom cavity filter was designed and manufactured, shown in Fig. 2.

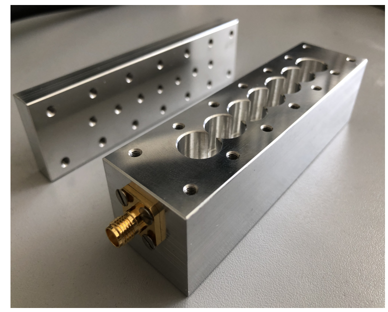

Figure 2: Custom Design Cavity Filter.

The measured S-parameters are shown in Fig. 3. The performance of the manufactured filter meets the design specification for rejection at 11.9942 GHz, the total rejection at this frequency is −69.19 dB. The transmission in the passband is lower than for an ideal filter but is comparable to the simulation which suggested −10 dB.

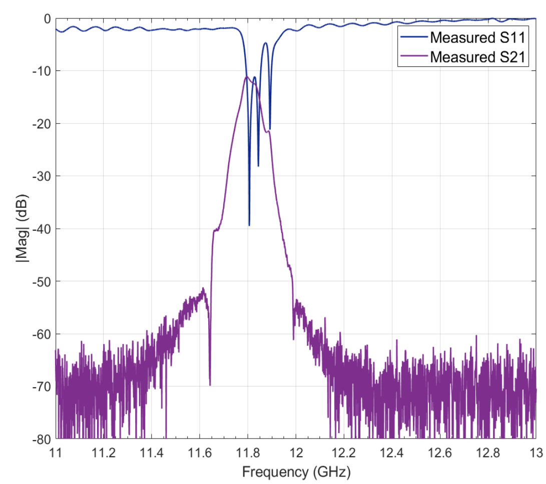

Figure 3: Measured S-Parameters of the 11.806 GHz Custom Designed Cavity Filter.

The cavity filter is positioned at the output of the up-convertor. This combination results in complete rejection, with respect to the noise floor of the measurement, of unwanted frequencies at 11.9942 GHz and 12.182 GHz. Figure 4 gives the LO spectrum and it is seen that 70 dB suppression has been achieved at all the sidebands.

Phase Noise Results

The phase noise profile of the up-convertor closely resembles that of the master oscillator. The additive phase noise at 11.9942 GHz is due to the increase in frequency. The noise to carrier ratio increases by n^2 where n is the multiplication factor, in this case n = 4 so the phase noise should increase by 16 dB, the average increase in phase noise is 14.54 dB.

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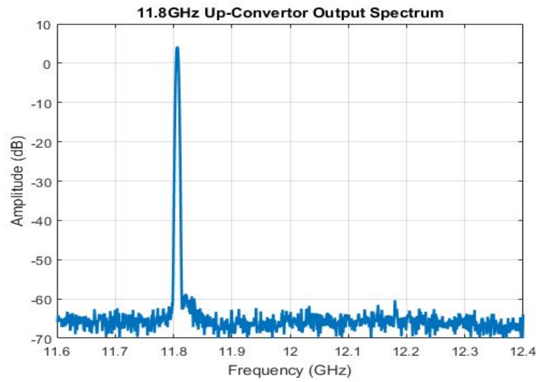

Figure 4: 11.8 GHz Spectrum.

Crucially, the phase noise performance of the up-convertor is significantly improved compared with the PLL as shown in Fig. 5.

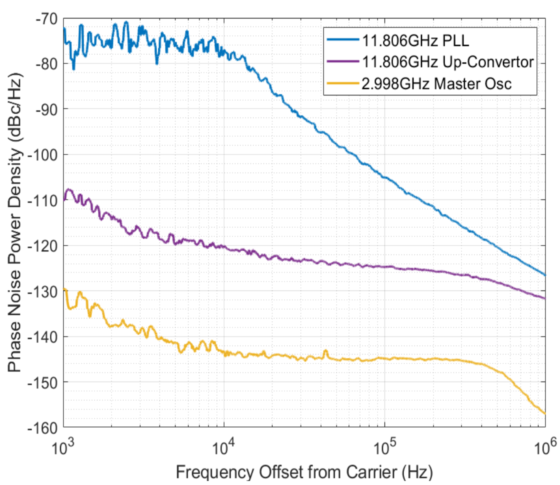

Figure 5: Phase Noise of the X-band Local Oscillators (PLL and Up-Convertor) and the S-Band Master Oscillator.

KLYSTRON OPERATION

The upgrade included the re-writing of the LabView code, integrating the new LLRF system and changes to the peripheral systems. This was completed in late 2020 and high power testing began in December 2020 with the conditioning of a 50 MW klystron. Both the up-convertor and the PLL were tested alternatively. A 150 ns RF pulse was generated using the new LLRF system, the X-Band low power pulse is amplified using a 1 kW TWT followed by a VKX-8311A CPI klystron.

Phase noise and jitter both indicate the stability of a signal, and are interrelated. Specifically, phase noise is the instability of a frequency expressed in the frequency domain, while jitter is fluctuation of the signal waveform in the time domain. Phase noise indicates fluctuations in the phase of the signal. Therefore, when observed in the time domain, it appears as waveform jitter. The variation in the phase across the flat top of the RF pulse is lower when using the up-convertor, rather than the PLL, to generate the LO. This is shown in Fig. 6 which shows the standard deviation of the phase across the RF pulse. This is due to the low phase noise of the up-convertor. Phase noise added by the local oscillator during down-conversion will appear as jitter on the RF pulses.

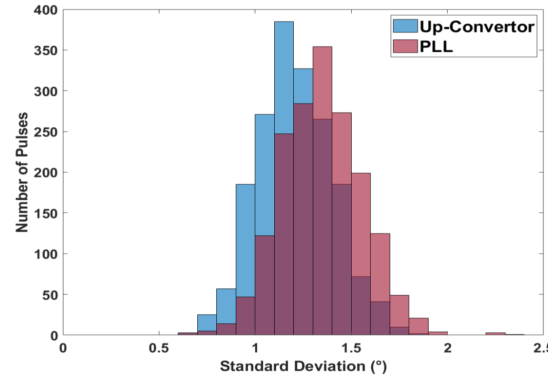

Figure 6: Comparison of the Standard Deviation of the Phase across 150 ns RF Pulses when using the PLL and the Up-Convertor to produce the Local Oscillator.

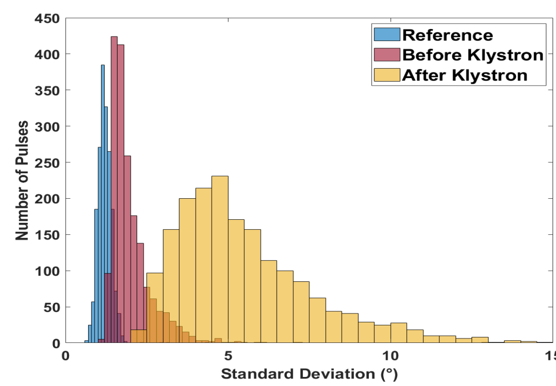

Figure 7: Comparison of the Standard Deviation of the Phase across 150 ns RF Pulses when using the Up-Convertor.

Figure 7 shows that the klystron is the dominant source of phase instability. The phase jitter of the LLRF system is lower than the phase jitter induced by the klystron which will enable an accurate estimation of klystron jitter.

CONCLUSION

A single side-band up-conversion system has been successfully employed to produce a low phase noise X-band local oscillator signal. The single-sideband up-convertor and cavity filter combination produce significantly lower phase noise results with respect to the original PLL system. The average reduction in phase noise close to the carrier (up to 10 kHz) is 40.64 dB. Also the phase noise floor is reduced by 6.38 dB (at offset frequencies above 100 kHz).

In high power measurements, the improved phase noise of the up-convertor translates to a reduced phase jitter over the flat-top of the reference RF pulse.

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