ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB063

CONNECTION OF 12 GHz HIGH POWER RF FROM THE XBOX 1 HIGH GRADIENT TEST STAND TO THE CLEAR ELECTRON LINAC

A. V. Edwards[1]*, N. Catalan Lasheras, S. Gonzalez Anton, G. Mcmonagle, S. Pitman, V. del Pozo Romano, B. Woolley, CERN, Geneva, Switzerland
A. Dexter, Lancaster University, Lancaster, UK
[1]also at Lancaster University, Lancaster, UK

Abstract

A new RF system is being established at XBOX1 to drive two 100 MV/m CLIC structures in the CLEAR electron linac. In the past, these structures had been powered by RF from PET structures excited by a drive beam. This drive beam is no longer available. The upgrade will reroute power from the 50 MW klystron and pulse compressor which was previously used to power the structure in XBOX1. During the upgrade, the LLRF system will be optimised to improve the modulation of the output signals and down-mixing of the returning signals to obtain accurate phase and amplitude information. The design of the improved LLRF and software, along with phase noise measurements and comparisons with the old system are made in this paper.

INTRODUCTION

The Compact Linear Collider (CLIC) project has led to investment in X-band technology at CERN [1]. Three X-band test stands provide high power pulses at 11.9942 GHz to condition accelerating structures and other high power RF components. XBOX1, the first of the three test stands, was designed and commissioned in 2012 [2]. Since commissioning there has been little change to the infrastructure at XBOX1. In comparison, at XBOX2 [3] and 3 [4] developments have been made to the low level RF (LLRF) and data acquisition software. CLEAR is the new title of the former CLEX linac at the CLIC test facility (CTF3) at CERN [5]. Previously two TD26 'super-structures' were installed in CLEX to test the two beam concept [6]. Following the test, one of the structures has remained in the beam line without a high power connection. The drive beam has since been decommissioned, however, there is still a requirement to power the cavity, this will be done with the XBOX1 klystron. Parallel to the development of a drive beam based CLIC [7], a klystron based CLIC has been proposed where high-power X-band klystrons power the accelerating structure directly, ("klystron based CLIC"). The plan is to connect the 50 MW klystron from XBOX1 to the TD26 'super-structure' at CLEAR and to upgrade the XBOX1 electronics and software to align them with the other X-band test benches. This involves rewriting the acquisition software and completely replacing much of the low level electronics. A 25 m line of low loss over-moded waveguide has been installed to transport the power from the XBOX1 pulse compressor to the 'super-structure' in CLEAR. The line is currently under vacuum and terminated with two high power loads. The waveguide and components will be conditioned to high power before connecting to the structure in order to minimise downtime for the CLEAR linac and ensure the conditioning of the 'super-structure' is not limited by any of the components in the line. The software is being rewritten so that all of the test stands will use almost identical control and conditioning algorithms.

* Amelia.Edwards@cern.ch

ORIGINAL XBOX1 LLRF

The current XBOX1 pulse forming network (PFN) is shown in Figure 1. The PFN contains many clock and trigger signals with multiple timing cards and level conversions spanning over multiple electronics racks and occupying multiple crates, the system is unnecessarily complicated. Originally XBOX1 acquired IQ demodulated signals during breakdown pulses and used log detectors for fast interlock responses and real time monitoring. However, the IQ demodulation was low resolution and is now non-functional. The remaining diodes and log detectors can only obtain amplitude information for analysis. In the upgrade, the PFN will be replaced by a National Instruments (NI) modulation card in the PXI chassis [8]. The clock and trigger system will be replaced by a single NI timing card [8]. All clocks and triggers will be generated from this with the exception of the master oscillator from CLEAR and a 'Start RF' trigger to synchronise correctly with the beam. Hence, after the upgrade the circled components in Fig. 1 will be replaced by NI card and single electronics crate.

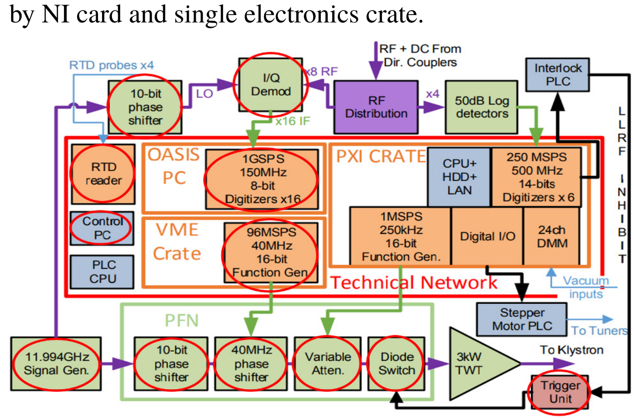

Figure 1: Original XBOX1 LLRF, circled components to be re-moved by upgrade.

LLRF UPGRADE

The XBOX1 system must allow for synchronisation with the CLEAR linac so that the high-power RF pulses can be

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB063

correctly phased with the beam. For this reason, both systems must share the same master oscillator, this is unlike XBOX2 and XBOX3, which do not have beam and thus are not constrained in this way. The upgrade will introduce frequency mixing schemes into XBOX1, the front end will mix the 2.9985 GHz CLEAR master oscillator up to 11.9942 GHz RF with pulse modulation. The receiver will down-mix the returning RF signals with a local oscillator (LO) frequency of 11.9942 GHz in order to produce a low intermediate frequency (IF) for digital sampling.

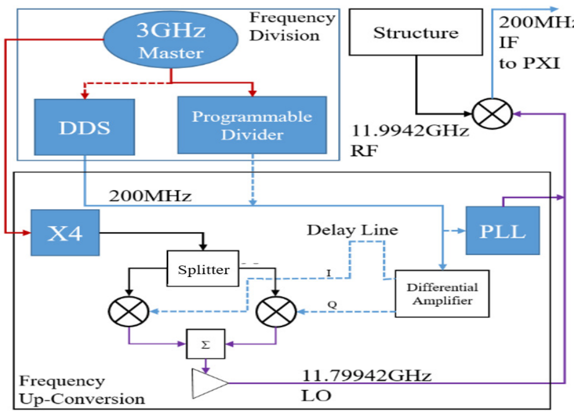

Figure 2: Block schematic of the the new LLRF in XBOX1.

The LO will also be synthesised from the 2.9985 GHz CLEAR master oscillator so that measured phase at the receiver is determined with respect to the drive beam and linac phase. The new LLRF scheme is shown in Fig. 2.

Selection of Intermediate Frequency

The selection of the IF is driven by several parameters: the bandwidth and specification of the acquisition cards, the timing resolution required for breakdown localisation and the requirement to be able to generate the LO from the 2.9985 GHz master oscillator.The rise time of the RF pulses is an indicator of the bandwidth required in order to accurately represent the signal without loss of resolution on the rising edge. The rise time will be considered to be the time taken for the signal to rise from 10% to 90% of its peak value. The rise time can be converted to a bandwidth using the following approximation:

$$t_r(\mathrm{s}) = \frac{0.35}{BW(\mathrm{Hz})} \tag{1}$$

This will enable us to select an intermediate frequency that has sufficient bandwidth to accurately reconstruct the RF pulses [9]. The incident power pulses have a rise time of approximately 7.2 ns, [7] the minimum bandwidth required to reconstruct this rising edge is 48.6 MHz. However, for breakdown localisation is it necessary to be able to detect changes over a smaller time frame than the rise time of the RF pulses. More detailed information on breakdown localisation techniques can be found in [10]. A CLIC 'super-structure' has a $3\pi/2$ phase advance and a non-constant group velocity of between 0.0165$\boldsymbol{c}$–0.0083$\boldsymbol{c}$ [7]. In order to be able to differentiate between cells the time taken for the RF to traverse one cell should correspond to one cycle of the RF. For a group velocity is 0.01$\boldsymbol{c}$ and cell length of 5.5 mm, the time taken for the RF to traverse one cell is approximately 1.83 ns. However, using the phase information the breakdown location can be localised to within three cells [11]. The time taken for the RF to traverse three cells, for a group velocity of 0.01$\boldsymbol{c}$ and cell length of 5.5 mm, is approximately 5.49 ns which would translate to a bandwidth of 91.1 MHz. Thus the chosen IF is 199.9 MHz. This frequency can be synthesised by dividing the 2.9985 GHz master oscillator by 15. The choice of IF and sampling scheme also integrate with the specifications of the oscilloscope cards which are currently used in XBOX1. The NI PIXe-5162 [8]. This is a 4channel, 10 bit, 5 GS/s digitizer. In this case, the analog to digital convertor (ADC) is capable of IQ sampling the IF as the sampling rate is above 800 MS/s and the bandwidth is above 200 MHz. In order to produce an IF frequency of 199.9 MHz the 11.9942 GHz RF signals will be mixed with an LO of 11.7942 GHz.

Frequency Division of 2.9985 GHz to 199.9 MHz

Frequency division of the 2.9985 GHz master oscillator is required for two reasons. Firstly, to provide a suitably low frequency input to synthesise the LO of 11.9742GHz. Secondly, as a source for producing the 799.6 MHz sampling clock for data acquisition. The 2.9985 GHz will be divided by 15 to produce 199.9 MHz.

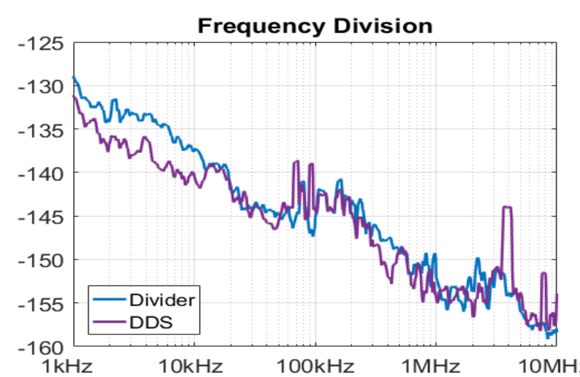

Figure 3: Phase noise results from DDS and PD at 199.9 MHz centre frequency.

Two frequency division methods that will be compared, these are a programmable divider and a Direct Digital Synthesiser (DDS). The programmable divider (PD) is the HMC705 [12], it is an analog chip which can produce integer division ratios between 1 and 17. A DDS produces analog waveforms from a digital, time varying signal. The DDS is the AD9914 [12], which contains a 12bit digital to analog convertor (DAC) allowing for fine frequency control. Figure. 3 shows a comparison of the single sideband phase noise produced by the DDS and PD.

Frequency Up-Conversion from 199.9 MHz to 11.7942 GHz

The up-conversion step will take the 199.9 MHz as an input and synthesise 11.7942 GHz, which will be mixed with

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB063

the incoming 11.9942 GHz signals. The two up-conversion schemes are a Phase Locked Loop (PLL), and a single-sideband Up-Convertor. PLL's are a common method for producing a stable high-frequency output from a low-frequency input. However, PLL's can contribute significantly to the phase noise. A CERN custom designed PLL is used in both XBOX2 and XBOX3. The PLL for XBOX1 is the AD5355 which is a wideband PLL with integrated VCO. [12] The possible benefit of the single sideband up-convertor is reduced phase noise, with respect to a PLL, and possible removal of unwanted sidebands. Using two mixers, two quadrature phase shifters and an in-phase combiner creates trigonometric cancellation of the upper sideband. However, the efficiency of unwanted sideband rejection is limited by the amplitude and phase balance of the incoming IF. The up-convertor model is the ADRF6780 [12].

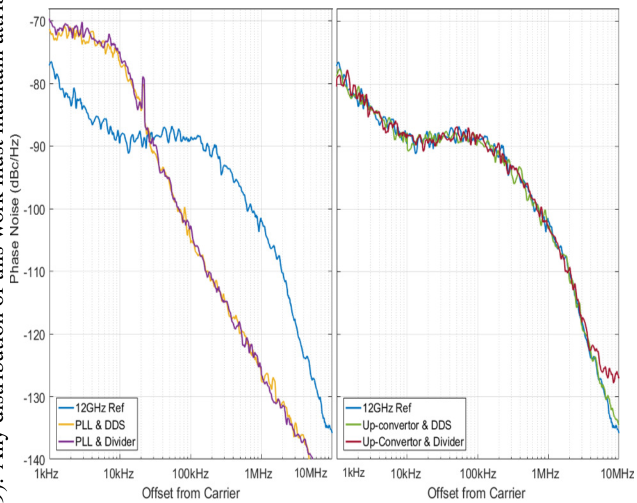

Figure 4: Phase noise results from PLL (left) and Up-Convertor (right) at 11.7942 GHz centre frequency.

Figure. 4 shows phase noise plots for the two up-conversion methods each with the 199.9 MHz input being produced from both the DDS and the PD. The up-convertor produces around 10 dB less phase noise close to the carrier. However, carrier suppression greater than −11 dB has not yet been achieved due to phase an amplitude imbalances on the input. The behaviour of the frequency up-conversion technique is the dominant influence on the phase noise.

11.9942 GHz Pulse Generation and Modulation

The upgrade will make two important changes to the production of the X-band frequency.

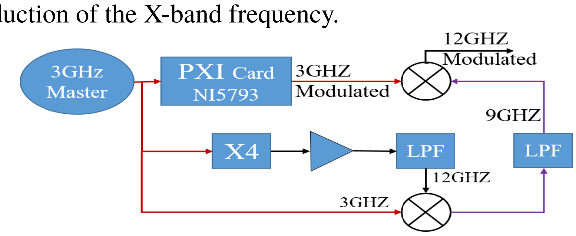

Figure 5: New PFN for XBOX1.

Firstly, production of the 11.9942 GHz from the 2.9985 GHz master oscillator will be produced locally at XBOX1. Secondly, the pulse forming network will be replaced with a PXI card, the NI5793 [8],which is currently used successfully in XBOX2 and XBOX3 for pulse forming and modulation. The new PFN is shown in Fig. 5

COMPARISON OF ACQUISITION

The new LLRF system was tested using a 1.5 μs, 2.9985 GHz modulated pulse. This pulse was fed into the mixing crate to be converted to a 11.9942 GHz pulse and mixed back down to 199.9 MHz.The pulse was also fed into the old LLRF system for comparison, the resulting pusle from both systems was digitized using the NI5162 acquisition card [8]. Both signals were sampled at 799.6 MHz for 1.8 μs and filtered during post-processing using a bandpass filter with a 40 MHz bandwidth.

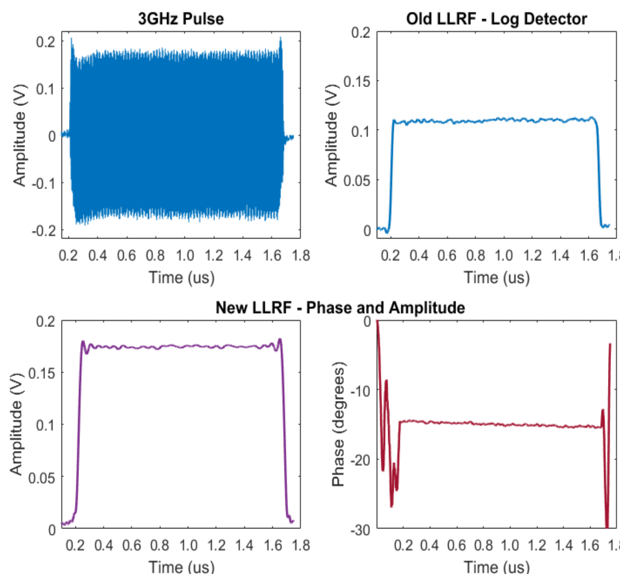

Figure 6: Top-Left: IF Directly Sampled. Top-Right: Log Detector. Bottom: IF Data Points with fitted line and demodulated

The results of demodulation are shown in Fig. 6 The old acquisition scheme used a log detector to collect amplitude information. The new LLRF system uses down-mixing to obtain both phase and amplitude information from the incoming RF signals.

CONCLUSION AND ONGOING WORK

The upgrade of XBOX1 and connection to CLEAR is ongoing. The software from XBOX3 is being adapted for use with XBOX1 for greater consistency across the high power test stands. The new LLRF for the upgrade of XBOX1 has been successfully designed and tested. The frequency division schemes produce comparable phase noise. The single-sideband up-conversion shows better phase noise performance than the PLL and thus will be implemented in the upgrade. However, more work is needed to achieve a higher level of suppression of the carrier frequency. This will be combined with the design of a high-Q, narrowband cavity filter centred around 11.7942 GHz.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPRB063

REFERENCES

[1] P. Burrows *et al*,. Eds., "Updated baseline for a staged Compact Linear Collider," CERN-2016-004,Geneva, 2016.

[2] W. Wuensch *et al.*, "Experience Operating an X-band High-Power Test Stand at CERN", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, pp. 2288–2290. doi:10.18429/JACoW-IPAC2014-WEPME016

[3] B. J. Woolley *et al.*, "High Gradient Testing of an X-band Crab Cavity at XBox2", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3242–3245. doi:10.18429/JACoW-IPAC2015-WEPHA057

[4] M. Volpi *et al.*, "High Power and High Repetition Rate X-band Power Source Using Multiple Klystrons", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 4552–4555. doi:10.18429/JACoW-IPAC2018-THPMK104

[5] K. N. Sjobak *et al.*, "Status of the CLEAR Electron Beam User Facility at CERN", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper MOPTS054, this conference.

[6] A. Samoshkin, D. Gudkov, A. Solodko, and G. Riddone, "CLIC Two-Beam Module for the CLIC Conceptual Design and Related Experimental Program", in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastian, Spain, Sep. 2011, paper TUPC008, pp. 1003–1005.

[7] M. Aicheler *et al.*, Eds., "A Multi-TeV Linear Colider based on CLIC Technology: CLIC Conceptual Design Report," CERN, Geneva, 2012.

[8] National Instruments, http://www.ni.com/en-us.html

[9] M. Buzuayene, "Rise Time vs. Bandwidth and Applications," Morgan Hills, CA, USA: Anritsu Corporation, 2008.

[10] J. Giner Navarro, "Breakdown studies for high gradient RF warm technology," University of Valencia, 2016.

[11] A. Tropp, "Studies of vacuum discharges in the CLIC accelerating structure," Lund University Faculty of Engineering, 2016.

[12] Analog Devices, https://www.analog.com/en/index.html