HIGH POWER X-BAND GENERATION USING MULTIPLE KLYSTRONS AND PULSE COMPRESSION

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Abstract

CERN has constructed and is operating a new X-band test stand containing two pairs of 12 GHz, 6 MW klystrons. By power combination through hybrid couplers and the use of pulse compressors, up to 45 MW of peak power can be sent to any of 4 test slots at pulse repetition rates up to 400 Hz. The test stand is dedicated to RF conditioning and testing of high gradient accelerating structures for the CLIC study and also future X-band FELs. Operations have been ongoing for a few months, with initial operation dedicated to control algorithm development. Significant progress has been made in understanding the unique challenges of high power RF combination and phase switching using RF hybrids.

INTRODUCTION

Recent studies have found that high-gradient accelerating structures such as those used in the CLIC project [1], take many hundreds of millions of pulses to condition to nominal operating conditions [2]. Within the CLIC project there is an extensive program aiming to test 40 structures by 2019 in order to optimize the design and fabrication of CLIC prototypes. At the same time, the light-sources community has expressed an increasing interest in 12 GHz accelerating structures for both acceleration and diagnostics. Therefore we are working towards increasing the test capacity in this frequency and doing so at a high repetition rate in order to reduce the time needed to condition structures.

To this end CERN has built three test facilities called Xbox1, Xbox2, and the newest and subject of this report, Xbox3 [3, 4]. Xbox1 and Xbox2 use similar technologies to the original klystron-based test facilities in Japan and the US. These use high peak power, 50 MW klystrons, which require modulators capable of producing 450 kV or more. However, Xbox3 uses a combination of low peak power, 6 MW klystrons. High peak powers are achieved by combining the output power of multiple klystrons and using pulse compression [5]. This process allows the production of 50 MW, 200 ns pulses at much higher repetition rates than would be possible with the single, 50 MW klystrons used in previous Xboxes. In this paper, we will describe the combination scheme used in Xbox3, the LLRF and control system and the experience of commissioning the facility under high power.

COMBINATION SCHEME

CLIC prototype structures require 40-50 MW of RF power with pulse widths up to 250 ns. Xbox3 uses Toshiba E37113 klystrons and ScandiNova K1 modulators which can each produce 3.5 us pulses with 6 MW of peak power. The pulse repetition rate can be increased up to 400 Hz. The original Xbox3 layout combined four klystrons through a chain of hybrids to reach the required power for a test bench [6]. However, by combining only two of these klystrons and using pulse compression to multiply the peak power by a factor four, power levels of 50 MW and pulse widths of 250 ns can be achieved. By changing the phase difference between the two klystrons, the power can be split in any ratio to either of the hybrid outputs. Under normal operating conditions the power is sent to each slot in an alternating fashion. The change from a 4x1 to a 2x2 system allows for higher repetition rates for each test slot (up to 200 Hz as opposed to 100 Hz). More practical advantages of the 2x2 system include reduced downtime due to klystron failure or replacement; if a single klystron fails a pair of klystrons will remain functional at full power.

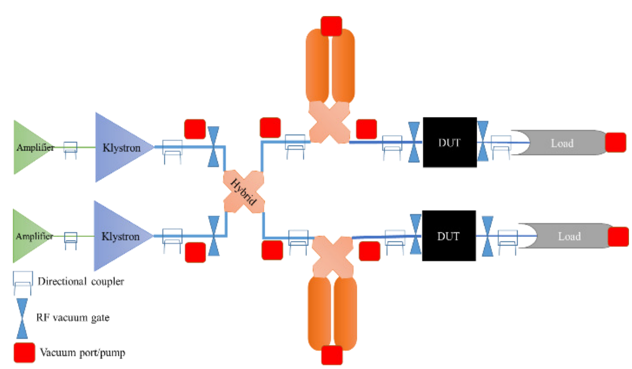

Figure 1: Schematic of the high power RF network of half the Xbox3 facility.

After the hybrid combination each line has a pulse compressor, test slot for the DUT and a RF stainless steel load to terminate the waveguide network. Directional couplers are placed at critical locations in the network for monitoring purposes. Vacuum pumping ports and RF vacuum gates complete the network. A layout of the final Xbox3 configuration is shown in Figure 1.

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LOW LEVEL RF

As shown in Figure 2, the LLRF and control system is based on a National Instruments PXI crate. Each pair of klystrons shares one PXI crate and controller. The RF drive signals are produced using NI 5793 IQ generators at 2.4 GHz. The arbitrary IQ signals are externally up-converted to 12 GHz. For RF signal acquisition, 12 GHz signals from the directional couplers are down-mixed to an intermediate frequency (IF) of 400 MHz. The IF signals are digitised at 1.6 GSPS (4 times oversampling) or at 228.57 MSPS (4th Nyquist zone under sampling). FPGAs are then used to perform IQ demodulation. The oversampled channels are used to sample the signals adjacent to the DUT, where the highest time resolution is desired. To reduce the number of digitisers needed, these signals are multiplexed between each pair of DUTs. The under sampled channels are used to sample all other forward propagating signals and are not multiplexed. All reflected signals except those from the DUTs are acquired using RF logarithmic detectors. These detectors directly rectify the 12 GHz signals and have a dynamic range of 45 dB. The high dynamic range allows these detectors to detect low-level steady state reflection and also high-level reflections during breakdown events.

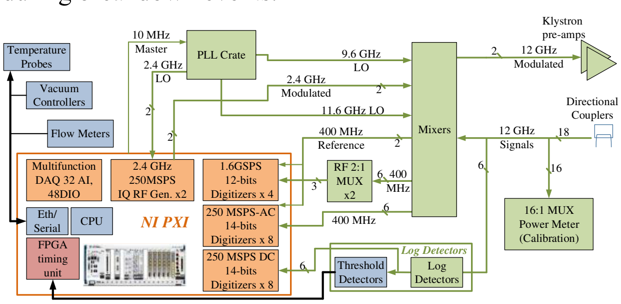

Figure 2: Schematic of the LLRF and signal acquisition.

The digitised signals are used as inputs into the various control loops, adjusting the power delivery to the DUTs. The controller simultaneously monitors vacuum levels, temperatures and interlocking systems. By running a real-time operating system on the PXI crate controller, 16 RF channels per test slot i.e. 32 RF channels per PXI crate can be processed at repetition rates of up 400 Hz. This represents a 20 fold increase in the data throughput compared to Xbox1 and 2. This increase in data throughput was made possible by an almost full re-write of the Xbox2 PXI's code.

CONTROL ALGORITHMS

There are several control loops that ensure the successful operation of the test stand and to operate two klystrons and two test slots independently. For power level control there are four nested loops as shown in Figure 3. The lowest level loop controls the power output of the second (or slave klystron) by adjusting IQ generator 2, using the measured value of the first (or master) klystron output as the process variable. The second loop changes the output from IQ generator 1 to change the master klystron's output power. The third loop adjusts the set point power of the master klystron depending upon the power level requested by the DUT. Finally, the power input of the DUT is controlled using either the breakdown rate or vacuum conditioning algorithm. There are two sets of the four nested loops; one set for each DUT. Each set of loops is executed on alternating pulses.

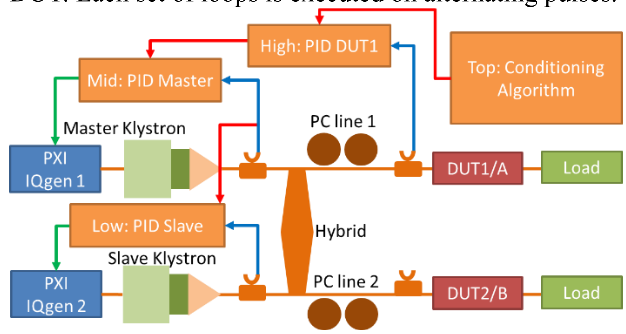

Figure 3: Schematic of the power control loops for line 1/A.

The conditioning algorithms have been adapted from those used in the other Xboxes [3,4]. The vacuum conditioning algorithm has been modified such that the vacuum channel used as the process variable can be selected from all available pumps in the system. The BDR conditioning algorithm has been updated to use the pulse counter as its time base as opposed to timestamps used in the previous Xboxes. This allows the repetition rate to be changed without affecting the ramp speed in terms of number of pulses.

COMMISSIONING

At the time of writing two out of four test slots of Xbox3 has been fully completed with two CLIC prototype structures installed in lines C and D as shown in Figure 4. Commissioning of lines A and B will follow.

The commissioning of lines C and D started at the beginning of the year. This initial conditioning stage was performed with waveguides replacing the DUT's such that the system could be conditioned and verified at high power, before the testing program began. At this time only line C had a pulse compressor installed.

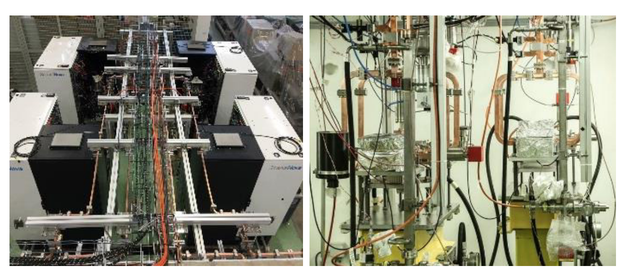

Figure 4: The modulators of Xbox-3 (left) and test slots C and D with structures installed (right).

Initial pulsing was performed at a low repetition rate of 15Hz, or 7.5 Hz per line. This was to verify that the phase switching of the IQ generators, the control loop synchronisation and the multiplexing inside the acquisition system was working as intended. After the performance of these subsystems had been verified, the repetition rate was increased to 200 Hz over a period of six weeks as shown in Figure 5.

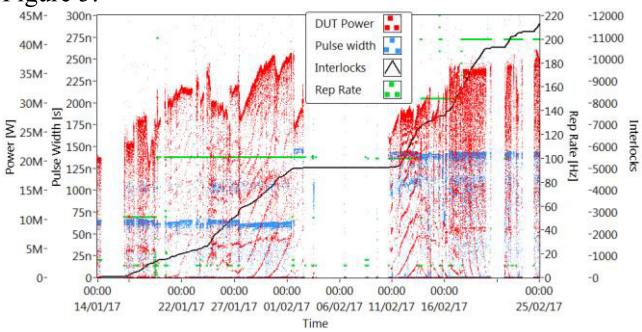

Figure 5: History plot of the commissioning of line C showing power, pulse length, accumulated interlocks and repetition rate over time.

During this time the power was increased initially using the vacuum conditioning algorithm due to outgassing of the waveguide components. The conditioning method was changed to the BDR algorithm once the main cause of interlocks was caused by arcing. Power levels of nearly 40 MW were reached with a compressed pulse width of approximately 150 ns.

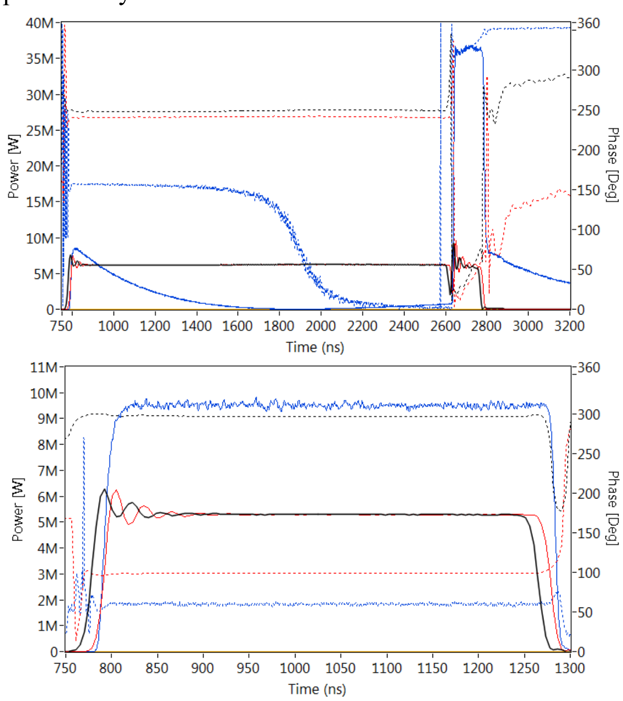

Figure 6: RF pulses during a ‘DUT C’ pulse (top) and ‘DUT D’ pulse (bottom). The DUT inputs and klystron C and D are shown in blue, black and red respectively. Solid lines show the power level in watts and dotted lines show the phase in degrees.

One of crucial issues with combining two klystrons is to make sure that their powers remain equal even during ramping and that the relative phase is well controlled. Figure 6 (top) shows the RF pulses from the klystrons and into the DUT C. Both klystrons’ output powers and pulse widths are identical at 6.3 MW and 2 us. The phase difference between the klystrons is also small. For the final 150 ns of the pulse the phase in both klystrons is flipped by 120° and ramped up by a further 60° in order to produce a flat compressed pulse with a peak power of 36 MW. To send power to DUT D the phase between the klystrons is changed by 180° as shown in Figure 6 (bottom). The pulse length and power level are also changed, demonstrating the flexibility of Xbox3. Line D has no pulse compressor installed, therefore the DUT pulse remains rectangular. There is approximately 10 % power lost in the combination and transport to the test slot due to waveguide ohmic losses.

The commissioning stage of lines C and D has now finished and two CLIC prototype structures have been installed; a TD24SiC (CLIC baseline accelerating structure with damping waveguides and absorbing material) and a T24 structure built by PSI [7].

CONCLUSION

The commissioning of half of the most recent X-band test facility at CERN has been completed at the time of writing. The combination of two low power RF sources into two high power testing slots has been successfully proven. In doing so, the complex LLRF and control software developed has been fully validated.

In the next months, the already installed structures will be tested and new prototype accelerating structures will be installed in lines C and D for high power test. After delivery of the new klystrons, lines A and B will be commissioned in the same way as described in this work. The high repetition rate of XBox-3 is already showing the significantly reduced time needed to condition accelerating structures as shown in [7].

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