COMMISSIONING OF XBOX3: A VERY HIGH CAPACITY X-BAND RF TEST STAND

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Abstract

The Compact Linear Collider (CLIC) beam-based acceleration baseline uses high-gradient travelling wave accelerating structures at a frequency of 12 GHz. In order to prove the performance of these structures at high peak power and short pulse width RF, two klystron-based test facilities have been put in operation in the last years. The third X-band testing facility at CERN (Xbox3) has recently been commissioned and has tripled the number of testing slots available. Xbox3 uses a novel way of combining relatively low peak power (6 MW) but high average power klystron units whose power is steered to feed four testing slots with RF to the required power with a repetition rate of up to 400 Hz. Besides the repetition rate, peak power, pulse length and pulse shape can be customized to fit the test requirements. This novel way of combining pulsed RF high power can eventually be used for many other applications where multiple test slots are required.

INTRODUCTION

The performance target for the normal conducting accelerating structures of a 3 TeV final energy version of CLIC is a maximum breakdown rate of $3\text{x}10^{-7}/(\text{pulse}\cdot\text{m})$ at the nominal average gradient of 100 MV/m in order to limit luminosity loss to less than 1% [1, 2]. An extensive program aiming at testing 40 structures by 2019 is being carried out to understand and control the RF breakdown rate in prototype CLIC accelerating structures. The original klystron-based test facilities in Japan and the US are being complemented by the construction of three new test facilities at CERN called Xbox1, Xbox2, and Xbox3 [3, 4]. Rather than using high peak voltages and currents in the klystrons as the previous two facilities, Xbox3 uses a combination of low peak power klystrons. The average power is recovered by increasing the pulse width and repetition rate. The required peak power is achieved by combining the output power of multiple klystrons and through pulse compression [5]. This process allows the production of 60 MW, 200-300 ns pulses at much higher repetition rates than would be possible with the single XL5 klystron used in previous Xboxes. In this paper, we will describe the combination scheme used in Xbox3. The two following sections will deal with the testing and commissioning of LLRF and control system. The last section will be dedicated to describe our experience during the global commissioning of the facility.

COMBINATION SCHEME

To recreate the power produced by the drive beam and Power Extraction Transfer Structure (PETS) into the CLIC accelerating structures, we require a rectangular pulse longer than 180 ns with a peak power of 60 MW. We use as in the previous test facilities pulse compression which can multiply the peak power by a factor four, when compressing a 3.5 µs pulse down to 300 ns [6]. The original Xbox3 layout combined four 6 MW power klystrons through a chain of hybrids to reach the required power for a test bench [7]. The phase into the klystrons is changed every pulse to direct the power to any of the four branches after the chain of hybrids. The high repetition rate (400 Hz) is used to feed the test benches sequentially with a final repetition rate of 100 Hz. However, given the good performance of the klystron/modulator system and the pulse compression obtained in Xbox2, we decided to separate the four-in-four system into two independent test facilities combining two-in-two. By construction, if any of the power sources fails, the operation of the full test facility is compromised. By building the Xbox3 as two separate facilities, we can double the general availability of the benches. The geometry and location of the elements in the waveguide network has been kept so that going back to a four-in-four operation is possible in the future by installing the two additional hybrids. The devices under test (DUT) are then placed after the pulse compressors with a stainless steel RF load at the output to terminate the waveguide network. Directional couplers, pumping ports and vacuum gates complete the network. A layout of the final Xbox3 configuration is shown in Fig. 1.

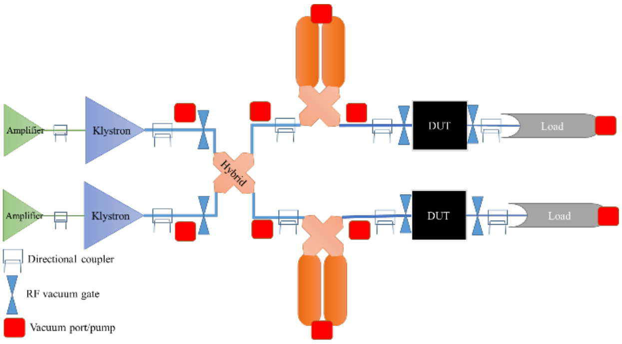

Figure 1: Schematic of the high power RF network of half the Xbox3 in two-in-two mode.

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POWER SOURCE

The klystron chosen for Xbox3 is a Toshiba tube model E37113. It works in combination with a Scandinova solid state modulator of the K1 type modified to give a performance as shown in Table 1.

Table 1: Klystron and Modulator Parameters

Parameter	Value	Units
Klystron		
Pulsed voltage	152	kV
Pulse current	92	A
Pulse length	5	µs
Peak RF power	6	MW
Modulator		
Pulse length (flat top)	5	µs
Max. voltage	170	kV
Max current	115	A
Max Pulse rep rate	400	Hz

The nominal peak RF power output was exceeded during the acceptance tests as the klystron was able to run in a stable conditions at a voltage of 160 kV, with a peak RF power output of 7 MW and a reduced 3 µs pulse width as shown in Fig. 2.

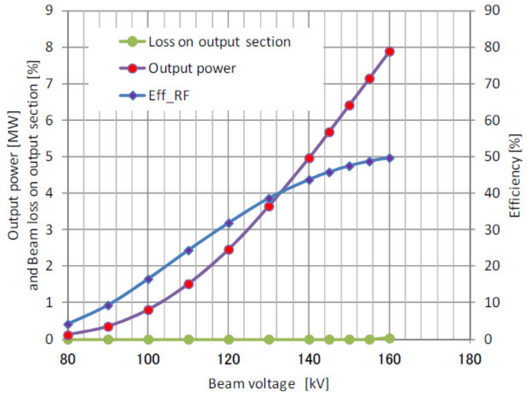


Figure 2: Power and efficiency vs. voltage curves for the Toshiba E37113 klystron.

As for the modulator, initial testing has shown a very good performance giving an excellent pulse flatness as seen in Fig. 3 and pulse to pulse stability (both values <0.4%).

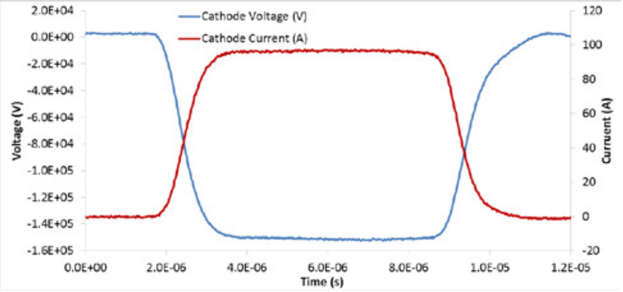
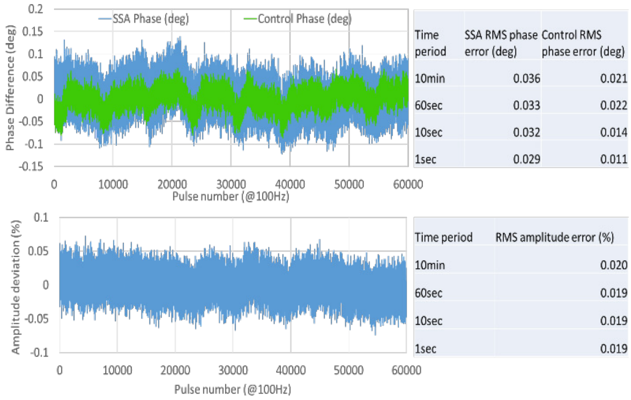


Figure 3: Klystron cathode and current Pulse flatness is <0.4% rms for both magnitudes.

A newly developed solid state amplifier (Microwave Amplifiers AM61-12S-60-56-PR) is used to drive each of the klystrons. Phase stability was measured after arrival injecting a 2 µs, 12 GHz pulse into the 400 W solid state amplifier (SSA) which was previously split and sent to the LLRF system's 1st input though a 2 m phase stable cable. The SSA output is sent to the 2nd input of the LLRF system. The input and output phase signals were subtracted to isolate the phase difference introduced by the SSA. Phase is averaged during 1.3 µs of the long central section of each pulse. The top plot of Fig. 4 shows the pulse to pulse phase RMS error for the SSA and for the control signal, the latter gives the measurement accuracy. The bottom plot shows the amplitude stability over time. The measured values correspond to the measurement accuracy and thus the RMS amplifier amplitude stability is better than 0.2 ‰.



Time period	SSA RMS phase error (deg)	Control RMS phase error (deg)
10min	0.036	0.021
60sec	0.033	0.022
10sec	0.032	0.014
1sec	0.029	0.011

Time period	RMS amplitude error (%)
10min	0.020
60sec	0.019
10sec	0.019
1sec	0.019

Figure 4: stability measurements of phase and amplitude for the new solid state amplifier.

LOW LEVEL RF

Figure 5 shows the LLRF and acquisition system of Xbox3. The system is divided into several distinct crate types. The first contains two PLL's. One PLL produces 2.4 GHz which is split into nine. Eight are output via SMA connectors while the last part is multiplied by 4 (to 9.6 GHz) and split into four outputs. The second PLL produces 2.9 GHz which is multiplied by four and split into four outputs. The second crate type is the mixing crate which performs different tasks. It mixes the 9.6 GHz and 2.4 GHz from the mixing crate to produce a 12 GHz CW reference signal. It also mixes the 2.4 GHz PXI modulated signal with the 9.6 GHz LO to produce a 12 GHz output which is fed to the klystron pre-amplifier. On the acquisition side, the 12 GHz signals from the directional couplers are down-mixed to 400 MHz using the 11.6 GHz LO. The down-mixed signals are digitised at 1.6 GSPS (4 times oversampling) before undergoing digital IQ demodulation using an FPGA inside the PXI crate. These down-mixed 400 MHz signals are used for monitoring and analysis. The final crate type is the log detector crate. This contains eight RF logarithmic detectors which directly rectify the 12 GHz signals which have a dynamic range of 45 dB and a bandwidth of 50 MHz. Their high dynamic range makes then suitable for the reflected signals, which are intended to detect breakdowns and interlock the system.

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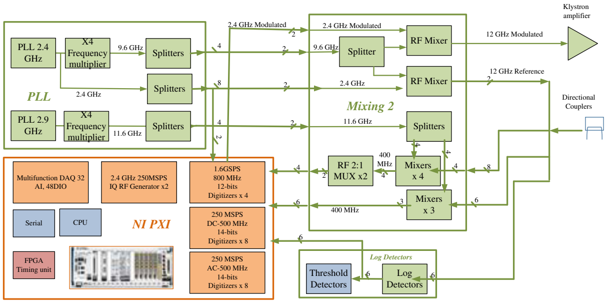

Figure 5: Schematic of the LLRF and signal acquisition.

The DUT time critical RF signals are digitised at 1.6 GSPS, which enables breakdown analysis to be performed with a sub-nanosecond time resolution. Whereas, a more relaxed 250 MSPS rate is used for the rest of the forward RF signals, (i.e. the signals to monitor and control the RF signal phase at the input of the hybrids and the leakage at the output.) Much of the LLRF scheme has already been successfully implemented at Xbox2 and extended and optimized for Xbox3. A final test was conducted to ensure that the PXI system and the two in-crate FPGA programmable RF signal generators could reliably switch the power from one output channel to the other at a rate of more than 400 times per second [8].

INTEGRATION AND COMMISSIONING

The modulators and klystrons are now in place and all the associated waveguide components, vacuum systems, measurement cables and interlocks are installed as can be seen in Figure 6. The commissioning of the test bench is being performed with waveguides replacing the DUT's so that the whole system can be conditioned and verified in high power RF before the testing program begins during the third quarter of this year. Pulse compressors will also be installed at a later stage due to their late availability. The LLRF hardware was designed, tested and installed at the test area in temperature-controlled racks. All RF signals and cables arriving to these racks have been calibrated prior to commissioning with RF.

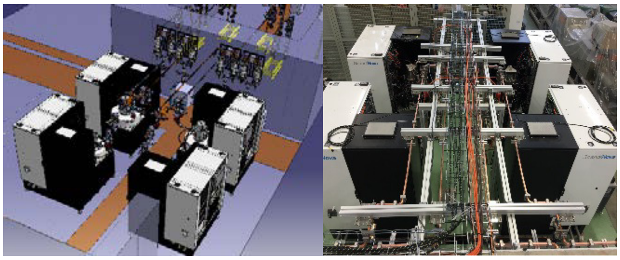

Figure 6: 3D integration of Xbox-3 (left) and as it is in real installation (right).

Commissioning of the system with RF started using the first half of Xbox3 (klystrons and modulators A and B). It was found at this stage that power from the SSA amplifier to klystron B was fully reflected. Further investigation showed that the input cavity is heavily detuned to 11.33 GHz. The klystron is now waiting for evaluation by Toshiba. Commissioning continued with the second half of the Xbox3 (klystrons and modulators C and D). Using the final operating LLRF and software, we switched the phase into both klystrons in alternating pulses at a repetition rate of 200 Hz. Figure 7 shows two consecutive pulses: power seen after klystron C and D and after the two branches of the hybrid named 3 and 4. The phase between klystrons has been changed by 180 degrees between pulses (top). We see an unexpected influence of the input phase into the final power produced by the klystron along the pulse. Calibration of the IQ modulators producing the original signal is still going on. The power from both hybrid branches however switches almost exactly with each phase change. We empirically found another set of initial phases which shows an exact cancellation of either channel 3 or 4. This proves the capability of selecting the power level into each testing line individually by only changing the input phase sent to each klystron. Further calibration of the LLRF signal generation is needed.

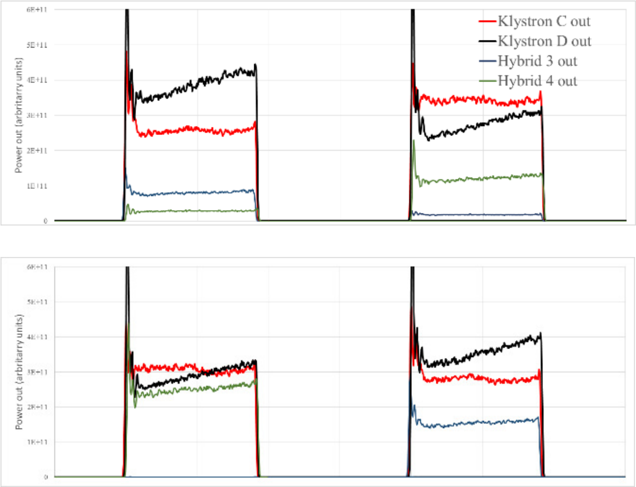

Figure 7: Measurements of two consecutive pulses after switching the input phase to the second klystron by 180 degrees at 200 Hz (top). For a different set of initial phases, the cancellation in one of the hybrid outputs is perfect (bottom). Signals from the hybrid branches are uncalibrated.

CONCLUSION

The commissioning of the last and most flexible X-band test facility at CERN is being completed at the time of writing. The combination of low power RF into a high power testing slot has been successfully proven that validated the LLRF and control software developed.

In the next months, three new prototype accelerating structures will be installed for high power test. The fourth line will be initially used to test other components required to validate the CLIC baseline. The high repetition rate of XBox-3 is expected to significantly reduce the time needed to condition accelerating structures.

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