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COMMISSIONING OF X-LAB: A VERY HIGH-CAPACITY X-BAND RF TEST STAND FACILITY AT THE UNIVERSITY OF MELBOURNE

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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 will been put in operation this year. The first Southern Hemisphere X-band Laboratory for Accelerators and Beams (X-LAB) is currently being commissioned at the University of Melbourne, it will house half of the CERN X-band test stand XBOX3, which has been renamed Mel-BOX. Like XBOX3, Mel-BOX employs a novel means of combining high average power but relatively low peak power (6 MW) klystron units to direct power to two testing slots with a repetition rate of up to 400 Hz. As well as the repetition rate, peak power, pulse length and pulse shape can be customised to fit the testing requirements. This novel means of producing high power and high repetition RF pulses can eventually be used for many other applications where multiple test slots are required. There are also plans for it to form the basis for developing a compact accelerator for medical or university applications, such as radiotherapy and compact light sources.

INTRODUCTION

To maintain luminosity with losses of less than 1% the maximum allowable breakdown rate for the normal conducting accelerating structures operating at 100 MV m^{-1} in the final 3 TeV version of CLIC [1] is 3×10^{-7}pulse^{-1}m^{-1}. An extensive research program aiming to test and characterise more than 40 prototype CLIC accelerating structures is being carried out, a major goal of which is to understand and control the RF breakdown rate. High gradient (X-band) klystron-based test facilities are currently located in Switzerland (CERN), Japan, the USA and now for the first time Australia (Melbourne). The Melbourne facility consists of half of the CERN X-band test stand system XBOX3, now renamed Mel-BOX [2] [3] [4]. Instead of using a single high peak power klystron, Mel-BOX combines the power from two low peak power klystrons. The testing capacity of a larger klystron system is recovered and exceeded by making use of the lowered power klystrons' longer pulse lengths 6 µs and higher repetition rates 400 Hz. The required peak power is maintained by combining the output power of the two klystrons and through pulse compression. Ultimately, this process allows for the production of 200 – 300 ns 50 MW pulses with a repetition rate of 400 Hz, higher than would be possible with a single klystron.

In this paper, we will present an overview of the design of Mel-BOX, Fig. 1, the results of the initial testing and commissioning of Low Level RF (LLRF) and control systems, and finally describe some of our experiences setting up and the commissioning the facility.

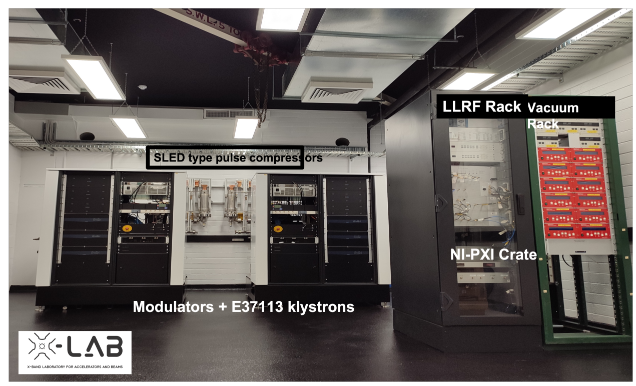

Figure 1: Layout of the new X-LAB and the configuration of the Mel-BOX test stands.

TEST STAND COMBINATION SCHEME

Pulse compression [5], as implemented at Mel-Box can increase the peak power by approximately a factor four, when compressing a 3.7 µs pulse down to 300 ns. This enables generation of a pulse with the properties of that would be required for CLIC in the drive-beam scenario. A layout of the final RF network of Mel-BOX configuration is shown in Fig. 2. As discussed above, to reach the 50 MW required for structure testing the power from the two Mel-Box klystrons is combined with a hybrid prior to the pulse compressors. The phase into the klystrons is swapped on each pulse to alternately direct the power to each of the the two pulse compressors and subsequent test lines. Thereby, splitting the 400 Hz repetition rate to feed each test stand at a final repetition rate of 200 Hz. Devices under test (DUT) are placed after the pulse compressors with a stainless steel RF load at the output to terminate the waveguide network and directional couplers, pumping ports and vacuum gates complete the network.

A short line has been built to allow for commissioning and conditioning of the klystrons, while work continues on

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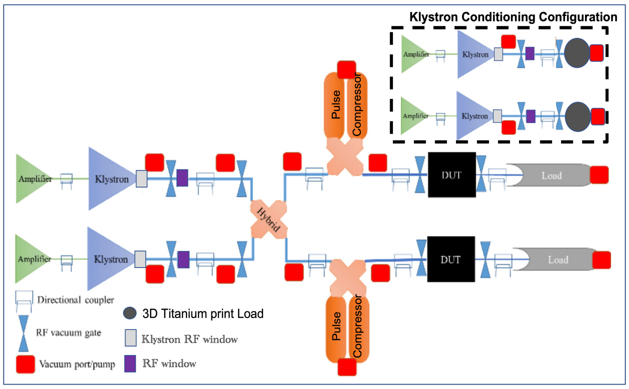

Figure 2: Schematic of the high power RF network of Mel-BOX. Top right, klystron conditioning schematic.

assembling the complete test stands, see top right of Fig. 2. The line consists of a directional couplers, vacuum pumps and 3D printed titanium spiral loads. Newly designed RF windows (E42170 Canon Electron Tubes & Devices) have been installed between the kylstrons and the rest of the waveguide network, Fig. 3, where they provide an extra layer of protection for the klystrons which have a long lead time for replacement, particularly so in Australia. The RF windows are installed and currently being conditioned along with the klystrons and 3D printed loads. They have been characterised at low power with the Vector Networks Analyzer, finding a reflection of (S_{11}) -30 dB and an attenuation (S_{21}) of 0.05 dB. Vacuum testing is good, they are presently installed in the line which is under vacuum at 10^{-10} mbar.

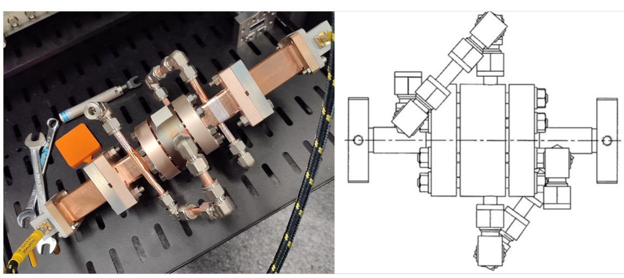

Figure 3: Compact, pillbox type, RF window with travelling wave in ceramic. Higher RF power capacity than the existing klystron window.

POWER SOURCE AND LOW LEVEL RF

Mel-BOX is using a Toshiba tube model E37113 installed in and powered by a Scandinova solid state modulator of the K1 type modified to give a performance as shown in Table 1. The klystron pulse length and power values are related to the ongoing conditioning process. These parameters have been chosen to optimise the ratio of extracted current and acceleration voltage ($I_{ex}/V_{acc}^{3/2}$), when the beam perveance corresponds to the minimum beam divergence.

In the case of the modulators, initial testing has shown very good performance with excellent pulse flatness and pulse to pulse stability (both values <1%). A solid state amplifier (SSA) (Microwave Amplifiers AM61-12S-60-56-PR) is used to drive each of the klystrons. The LLRF system that feeds

Table 1: Klystron and Modulator Parameters at the Nominal Voltage of 950 Volts

Modulator/Klystron C	Value	Units
Pulsed Voltage	151.1	KV
Pulse current	93.3	A
Modulator pulse length	4.7	µs
Klystron pulse length	0.15	µs
Peak RF power	5.5	MW
Modulator/Klystron D	**Value**	**Units**
Pulsed Voltage	154	KV
Pulse current	86.7	A
Modulator Pulse length	4.5	µs
Klystron Pulse length	0.1	µs
Peak RF power	5.5	MW

the SSAa is produces both a 12 GHz reference signal and a 12GHz output. On the acquisition side, the 12 GHz signals from the directional couplers are down-mixed and digitised before undergoing digital IQ demodulation using an FPGA inside a National Instruments PXI crate.

The DUT 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.)

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 Fig. 1 and 2. The commissioning of the klystrons is being carried out with the shorter waveguides system, top right Fig. 2. The aim is to condition and verify the majority of the system with high power RF before the testing program begins during the third quarter of this year. Before this can be done the pulse compressors, hybrid and large load will need to be installed.

So far, the LLRF hardware has been tested and is installed in temperature-controlled racks. All RF signals and cables to these racks, that are currently in use, have been calibrated. Both klystrons have been able to run stably at a voltage of 150 kV, with a peak RF power output of 5.5 MW and a reduced pulse width of 150 ns for klystron C and 100 ns for klystron D. This initial conditioning has been at a modest repetition rate of 50 Hz. Fig. 4 shows a screenshot of the control GUI with the input, output and reflected signal of the klystron D in ADC units. At this stage of conditioning interlocks are applied to the reflected power signals and vacuum levels only.

Vacuum behaviour of line C is shown in Fig. 5, the klystron vacuum (yellow line) is very stable, as expected, since we are running with short pulses and we do not therefore expect much arching within the tubes. Out gassing is

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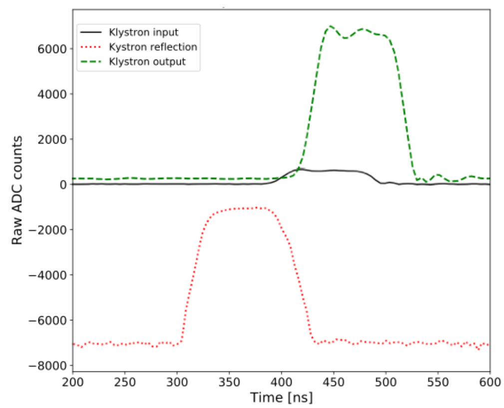

Figure 4: Klystron D; input and output klystron signals and reflected power.

observed in the 3D printed loads (red line), this is again expected as the 3D printed loads were not previously tested with high RF power. We also observe vacuum activity between the two RF windows (blue line), which also expected since the RF windows are being tested for the first time with high RF power. In practice, it is clear that this initial commissioning and conditioning program is conditioning the 3D loads and RF windows more so than the klystrons. Thus, in order to further condition the klystrons the 3D printed load will have to be replaced with larger loads that can accommodate the full length klystron pulses. The 3D printed loads were originally installed instead of the larger loads due to their smaller size which allowed for work on the lab to continue while conditioning began. The 3D printed loads are designed for pulse lengths of up to 200-300 ns. Once the loads are swapped the next step will be to increase the klystron pulse width up to the 3.7 µs pulse compressors are design for and continue conditioning.

As such we have successful conditioned the klystrons, RF windows and 3D spiral loads up to the maximum power of the klystrons with shorter pulse widths. The power ramp of klystron C during conditioning is presented in Fig. 6, recorded at 50 Hz repetition rate and 150 ns pulse width. The results for klystron D are similar however the 3D printed load experienced significantly more vacuum activity, which limited required limiting the pulse length to 100 ns.

Power calibration was performed with an RF pulse generator and detector used to measure the attenuation of the cables. Since, the test stands are not yet completely assembled, all components such us the directional couplers and adaptors have not yet been re-calibrated, instead we the calibrations as measured at CERN XBOX3 were used. Thus, uncertainty in the calibration could explain the lower than expected maximum power measurements (see Table 1) and the fact that Klystron C which is both newer and has a higher current measured at the cathode reaches the same 5.5 MW as Klystron D. Complete calibration of the final test stand will resolve this discrepancy.

Fig 7 shown the power gain curves and the phase stability of both klystrons as a function of the drive power (SSA). In both case the phases are very stable, with the phase spikes

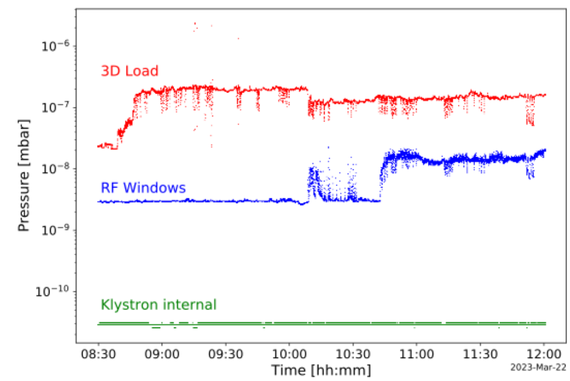

Figure 5: Klystron C line Vacuum trends, inside the klystron (yellow) between the RF windows (blue) and at the load (read).

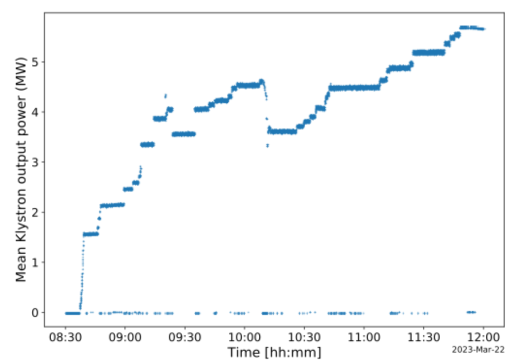

Figure 6: Klystron C Power ramp as a function of time. Klystron C conditioning plot at 150 ns pulse width and 50 Hz repetition rate.

observed at low power being a consequence of the jitter due to the small pulse widths.

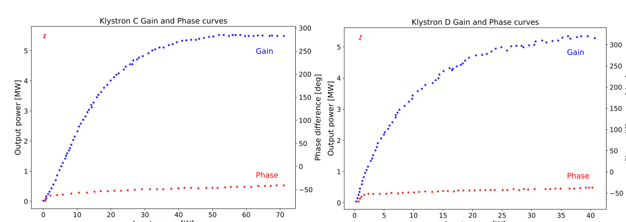

Figure 7: Gain and phase curves of klystron C (left) and klystron D (right) as a function of the drive power (SSA) at the nominal voltage.

CONCLUSION

The commissioning of Mel-Box the first high power X-band test facility in the Southern Hemisphere has begun. Successful testing of low level RF, control, data acquisition and high power RF systems shows that there have been no major issues as a result of shipping the equipment from CERN. Installation can therefore confidently continue and shortly larger RF loads will be installed enabling conditioning the klystrons up to the required 3-4 µs pulse. We are on track to commence testing prototype CLIC accelerating structures before the end of the year.

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