# X-LAB: a very high-capacity X-band RF test stand facility at the University of Melbourne

*Matteo* Volpi[1,*], *Paul J.* Giansiracusa[1], *Suzanne L.* Sheehy[12], *Roger P.* Rassoll[1], *Geoffrey N.* Taylor[1], *Paarangat* Pushkarna[1], *Rohan* Dowd[3], *Joel* Valerian[1], *Nuria* Catalan-Lasheras[4], and *Mark* Cherrill[5]

[1]The University of Melbourne, Melbourne, Victoria, Australia
[2]ANSTO, Kirrawee DC New South Wales, Australia
[3]Australian Synchrotron - ANSTO, Clayton, Australia
[4]CERN, Meyrin, Switzerland
[5]Australian National Fabrication Facility, University of South Australia

**Abstract.** The X-band Laboratory for Accelerators and Beams (X-LAB) has been commissioned at the University of Melbourne. One of the key projects within this laboratory involves re-homing half of the CERN high gradient X-band test stand, XBOX3, now known as Mel-BOX. This initiative aims to validate the performance of high-gradient travelling wave accelerating structures operating at a frequency of 12 GHz, which are a crucial component of the acceleration baseline for the Compact Linear Collider (CLIC). Mel-BOX will be employed to assess the performance of these accelerating structures under high power pulsed RF. As with XBOX3, Mel-BOX uses the combined power from two high average power klystron units to feed two test slots at a repetition rate of up to 400 Hz. Additionally, the parameters such as repetition rate, peak power, pulse length, and pulse shape can be tailored to meet specific test requirements. This method of generating high-power, high-repetition RF pulses holds promise for various applications necessitating multiple test slots. Moreover, there are plans to leverage this technology as a foundation for developing compact accelerators tailored for medical or university applications, including radiotherapy and compact light sources.

## 1 Introduction

A new laboratory is now operational at the University of Melbourne (UoM). This facility is the first high-power, high-frequency accelerator laboratory in the Southern Hemisphere, made possible by a collaboration between UoM, CERN and the Australian Nuclear Science and Technology Organisation (ANSTO). It is dedicated to testing high-gradient structure prototypes and RF components for the Compact Linear Collider (CLIC), as well as advancing ultra-precision manufacturing. The primary goals include designing and developing new accelerator technology, and providing local researchers and students with opportunities to make significant advances in within this space.

To maintain luminosity, with losses of less than 1%, the maximum allowable breakdown rate for the normal conducting accelerating structures operating at $100\,\mathrm{MV\,m^{-1}}$ in the final

*e-mail: m.volpi@unimel.edu.au

3 TeV version of CLIC is $3 \times 10^{-7}$pulse$^{-1}$m$^{-1}$ [1]. An extensive research program aiming to test and characterise more than 40 prototype CLIC accelerating structures is underway, 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 is home to half of the X-band test stand system XBOX3 that was previously installed at CERN, now renamed Mel-BOX [2–5]. Instead of using a single high peak power klystron, Mel-BOX combines the power from two low peak power rate klystrons, however the testing capacity of a larger klystron system is recovered and exceeded by making use of the longer pulse lengths up to $6us$ and higher repetition rates 400 Hz of the lower powered klystrons.

The required peak power is maintained by combining the output power of two 6MW E37113 CANON klystrons and with the use of pulse compression. Ultimately, this process allows for the production of ~50 MW flat-top pulses up to ~ 300 ns long at a repetition rate of 400 Hz, providing greater testing capacity than that a single klystron system at the same capital expenditure. Commercially available single klystron systems can reach the same power and pulse width but a limitation on the repetition rate of ~ 100Hz. The conditioning of high-gradient structures is dependent on the number of pulses, thus a high repetition rate drastically reduces conditioning time.

In this paper, an overview of the design of Mel-BOX (Fig. 1) and the first results from the conditioning of the two high power test lines are presented. A preliminary low power test of the high-gradient structures will also be shown.


**Figure 1.** Layout of the Mel-BOX bunker area. Two test stands with loads are shown on the left within the beamline zone. Klystrons, modulators, pulse compressors, Low Level RF (LLRF), and control systems are located on the bunker area (right).

## 2 Mel-BOX installation and commissioning

The modulators and klystrons, and all the associated waveguide components, vacuum systems, signal cables, and interlocks for Mel-BOX have been installed in the X-LAB. Some photographs of the lab are shown in figure 1. Mel-BOX uses a Toshiba klystron tube (model E37113) powered by a Scandinova solid-state K1 type modulator. The klystron pulse length and power values are tuned during the conditioning process based on a conditioning algorithm developed at CERN [6]. Initial testing of the modulators has shown excellent performance, with pulse flatness and pulse-to-pulse stability both within 1%.

The klystrons voltages 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.

Pulse compressors, hybrids, and loads have been installed. After a long shipping process, the pulse compressors were re-tuned and are now able to increase the peak power by approximately a factor of four, compressing a ~2.5 $\mu$s pulse down to ~80 ns. A layout of the final RF network configuration for Mel-BOX is shown in figure 2.

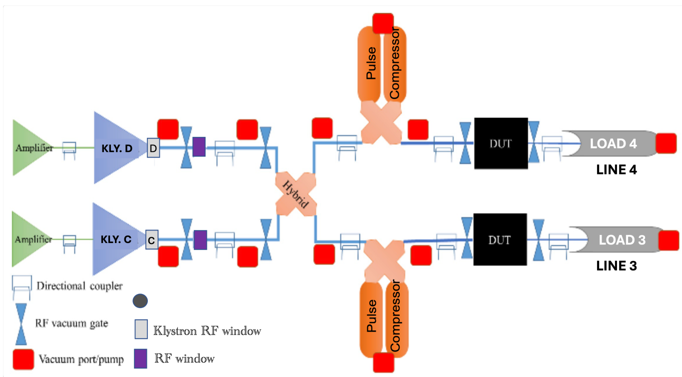


**Figure 2.** Schematic of the high power RF network of Mel-BOX.

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 in testing slots after the pulse compressors with a one-meter-long stainless steel RF load at the output to terminate the waveguide network [2]. Directional couplers for forward and reflected power measurements, pumping ports and vacuum gates complete the network.

Newly designed RF windows (E42170 Canon Electron Tubes & Devices) have been installed between the kylstrons and the rest of the waveguide network (see 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.

## 3 Line conditioning

The RF windows have been installed and are currently being conditioned, along with the waveguide network, pulse compressors and stainless steel loads. Table 1 summarizes the conditioning process to date, showing the peak power, average power and pulse length reached at each component. Transmitted and reflected power channels have been calibrated with power meters to approximately 0.1 dBm.

Prior to conditioning, the RF windows, pulse compressors, and loads were characterized at low power using a Vector Network Analyzer (VNA). Reflections below ~30 dB were observed, and no vacuum leaks were detected. These components are now installed and operating under vacuum at ~$10^{-9}$ mbar. The high-gradient structures will soon be installed, and preliminary low power tests results are presented in the final section.

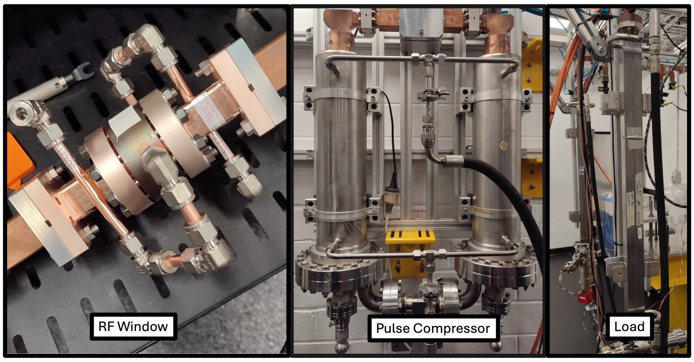


**Figure 3.** From left to right. The compact pillbox type RF window with travelling wave in ceramic. Pulse compressors, SLED-I. High power stainless steel loads.

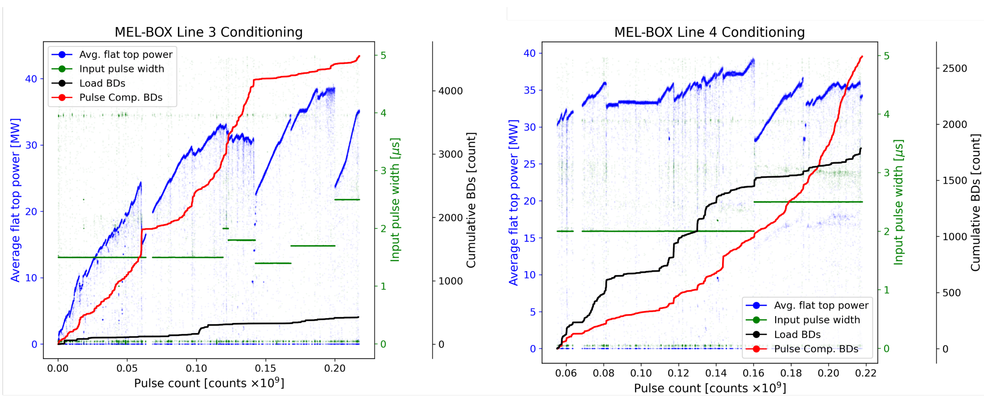


**Figure 4.** Conditioning plots of line 3 on the left and line 4 on the right.

Similar to structure conditioning, line conditioning involves gradually increasing power and pulse width in steps, provided there are no breakdowns (BD) or vacuum activity along the lines. The same structure conditioning algorithms is being used to condition the line and the various components [6]. In addition to the structure conditioning algorithm, the pulse width is manually increased through-out the conditioning process.

Breakdowns during the conditioning process are detected by setting thresholds on the reflected signals measured at the directional couplers installed along the lines (see Fig 2). Interlock flags are added to the data stream indicating which of the thresholds were exceeded. Based on these, and similar flags for vacuum activity, the location of breakdowns (BD) along the lines can be inferred. Thus, breakdowns can be attributed an associated component such as, the RF windows, pulse compressors and loads. The conditioning plots shown in figure 4 were produced with the aid of these flags. The plots show the average compressed power (flat-top) as a function of the number of pulses for Line 3 and Line 4, on the left and right, respectively. The number of breakdowns at the pulse compressors and loads is also indicated. The green lines shown the input pulse width before the compression. The pulse width is manually increased during the conditioning process once the maximum power at the previous pulse width has been reached. For example, this can be seen in the right plot of figure 4 around $1.6 \times 10^8$ pulses.

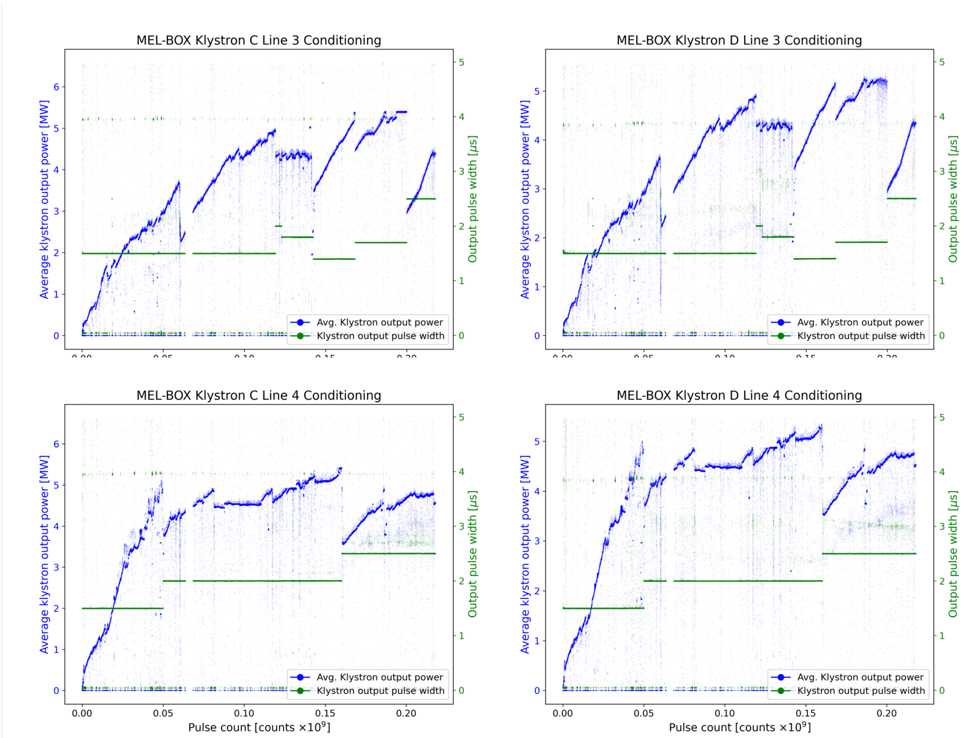


**Figure 5.** Klystron average output power, on the left klystron C on the right klystron D respectively.

The conditioning is dominated by breakdowns in the pulse compressors (red lines Fig. 4). Clusters of breakdowns are also observed drastically reducing the power. This is a consequence of the conditioning algorithm, which lowers the power when a given breakdown rate is exceeded, in order to reduce the likelihood of breakdown and prevent damage to the DUT. In this case the pulse compressors and loads, and in the near future the high-gradient structures. Negligible activity is observed in the load on line 3. Conversely, in line 4, load breakdowns contribute roughly equally to pulse compressor breakdowns suggesting that both are being conditioned. However, a short time after the pulse width is increased from $2\mu$s to $2.5\mu$s pulse compressor breakdowns begin to dominate the conditioning. Note that the conditioning plot on line 4 starts at $\sim$ 30 MW, and the data before are not reported because the line was not yet calibrated.

Presented in figure 5 are the klystron history plots showing the output power for each of the klystrons on each line during the conditioning of the wave-guide network. Note there are two plots for each klystron due to interleaving of pulses on each line, that is one pulse is directed to line 3 and the next to line 4. Prior to conditioning the waveguide network, the klystrons were conditioned independently [4]. The two klystrons used by Mel-BOX are different in age both in terms of date of manufacture and cumulative operating hours, with Klystron D being significantly older. As such, when operated at the same input voltage Klystron C has a significantly higher gain, approximately 10 %, with Klystron C reaching 6.2 MW and Klystron D reaching 5.5 MW. When operated together to feed the test lines the maximum power of each Klystron is limited to 5.5 MW by Klystron D, as such the output power in figure 5 does not exceed this value.

Table 1 summarizes the conditioning results of the components under test on both lines to date, showing the peak value of the uncompressed power, flat-top power and the associated pulse widths. Following from the discussion of klystron age above, the maximum power at the RF windows differs with the associated klystrons. This is a good result, considering that they were designed recently and this is their first high-power test outside the manufacturer's facility. The pulse compressors were previously used in operation at CERN and were re-tuned in Melbourne before their installation [7]. In agreement with the behaviour observed at CERN, the pulse compressors dominate the conditioning of both lines at high power levels and large pulse widths. To address this issue, a newly designed end cap for the cavity was developed at CERN and manufactured at the Australian National Fabrication Facility (ANFF) in Australia [6]. The results shown here were collected with the old end caps installed; the new caps will be installed and tuned during the next intervention on the line. Contrary to expectations, the pulse compressors have achieved about 40 MW on each line with a 2.5 $\mu$s pulse. This positive outcome is attributed to conditioning the lines without any DUTs, and thus the conditioning process is directed towards the other components following the most active, in this case the pulse compressors.

The one-meter-long stainless steel loads have also performed well. Typically, these loads are installed with high-gradient structures that absorb more than 50% of the input power, meaning they are rarely tested with more than $20-30$MW input power. In both lines, they have exceeded their designed average power of ~2KW, as shown in Table 1.

In summary, the RF windows have reached the maximum power able to be provided by the each of the klystrons. The pulse compressors are still undergoing conditioning, and even without replacing the cavity end caps, they have been operated with an input pulse of width of 2.5$\mu$s and produced a maximum output pulse of approximately 40 MW with an 80 ns flat-top. The stainless steel loads have been tested at ~40 MW peak input power and at average power above their design specification, no significant negative effects have been observed. The conditioning process has progressed steadily and the system appears ready for the installation of the first DUT.

**Table 1.** Conditioning summary table of components along the two lines. The conditioning it is still going on.

| Component | Pulse [$\mu$s] | Uncompressed Power [MW] | Flat-top (FT) [ns] | FT Peak-Power [MW] | Rate [HZ] | Av. Power [KW] |
|---|---|---|---|---|---|---|
| Win. C | 2.5 | 6.2 | 2500 | 6.2 | 200 | 3.1 |
| Win. D | 2.5 | 5.5 | 2500 | 5.5 | 200 | 2.75 |
| PC C | 2.5 | 10 | 80 | 40 | 100 | 3.2 |
| PC D | 2.5 | 9.5 | 80 | 38 | 100 | 3 |
| Load 3 | 2.5 | 10 | 80 | 40 | 100 | 3.2 |
| Load 4 | 2.5 | 9.5 | 80 | 38 | 100 | 3 |

## 4 Low power structure measurement

Two high gradient CLIC prototype TD24 structures have been shipped to Australia to complete the conditioning [1]. These structures were previously conditioned at CERN XBOX3 and reached accelerating gradients of 100 MV/m, which requires an input power of 42.2 MW. All going well, the lines will soon reach 42.2 MW and therefore the required power to reproduce the CERN results. These two specific structures are identical; the only difference is that TD24-N1 was baked before installation and high-gradient testing in 2019, whereas TD24-N2 was not, with the goal of determining the effects of baking on the conditioning process. The goal of reinstalling and retesting these structures at Mel-BOX is to determine the effect of long term storage (under $N_2$) on conditioned structures. In particular the reconditioning time and reproducibility of the high accelerating gradient.

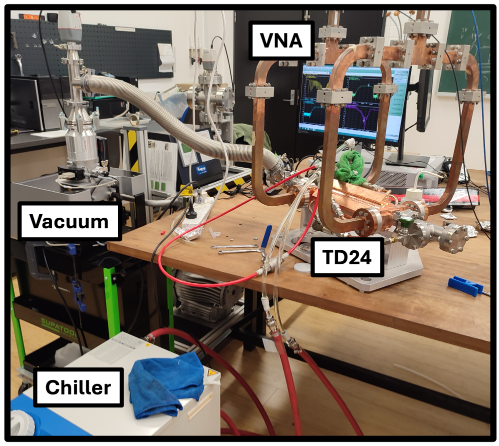


**Figure 6.** TD24 N2 structure testing setup: chiller set to 30°C, vacuum primary system, and VNA attached to the input $S_{11}$

The structures were manufactured, tuned, and tested in 2013. Bead-pull tests and tuning were performed in 2013 and again in 2020 after the high-gradient tests. They were subsequently packed and shipped to Australia.

TD24-N2 is currently undergoing low power testing at X-LAB, a photo of the setup can be seen in figures 7 and 8. The temperature of the structure is controlled at 30±0.1°C and is connected to a vacuum primary system. Low power transmission and reflection measurements have been collected with a two port VNA.

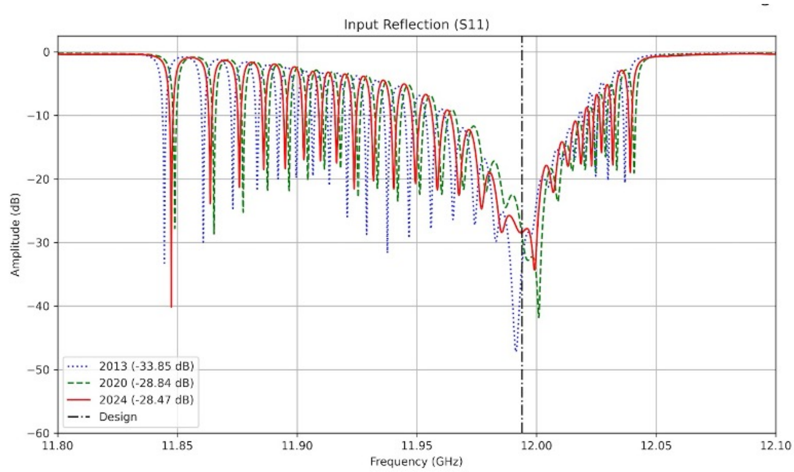


**Figure 7.** TD24-N2 structure input reflection for three different periods.

Results of low power measurements from 2013, 2020, and 2024 are shown in figures 7 and 8. No major variations between the current and previous measurements are observed, put differently no problems have arisen in shipping the structures to Australia. The reflection (left plot) is around -30 dB, the same value observed after the high-gradient testing at CERN. The transmission (right plot) is slightly higher due to the installation of the 3dB splitter and manifolds. CERN measurements were performed with a 4-port VNA, while in Melbourne, a 2-port VNA was use that required the splitter and manifolds. Bead-pull measurements to check the tuning of the single cells will be undertaken before the installation of the structure.

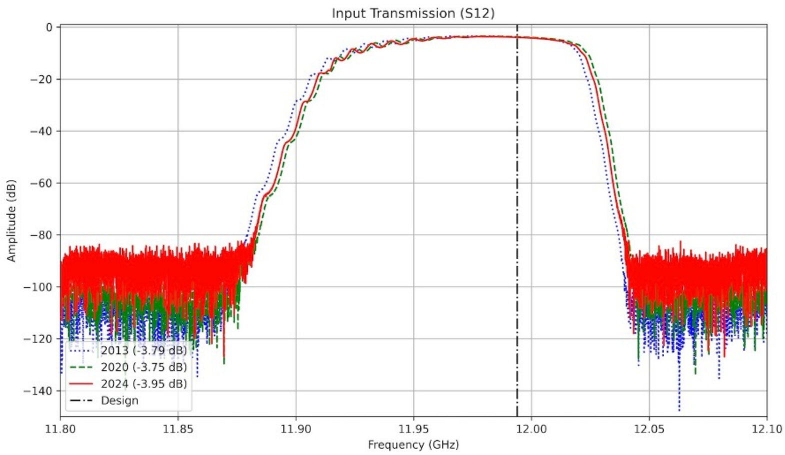


**Figure 8.** TD24-N2 structure transmission in the right plot for three different periods.

## 5 CONCLUSION

The line conditioning of Mel-BOX, the first high-power high gradient X-band test facility in the southern hemisphere, has begun. Successful testing of the low-level RF, control, data acquisition, and high-power RF systems indicates that there have been no major issues resulting from shipping the equipment from CERN. Low power testing of the CLIC prototype accelerating structures can therefore confidently continue, and shortly, they will be installed on the high-power lines, enabling conditioning up to the previous value of 42.2 MV/m. Mel-BOX is on track to finish testing the prototype CLIC accelerating structures before the end of the year.

## Acknowledgement

This work used the NCRIS and Government of South Australia enabled Australian National Fabrication Facility - South Australian Node (ANFF-SA). We would also like to extend our deepest gratitude to Rolf Wegner and Hikmet Bursali for testing and tuning the structures at CERN prior to their shipment to Australia.

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