HIGH-POWER TESTING OF X-BAND HIGH-GRADIENT STRUCTURES AND RF COMPONENTS AT THE MEL-BOX FACILITY

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Abstract

Mel-BOX, the reinstallation of half of CERN's XBOX3 test stand, has been operating at the University of Melbourne's X-LAB for several years. The facility provides 12 GHz high-power pulsed RF for the testing of X-band high-gradient accelerating structures and associated components relevant to the CLIC baseline. Two TD24 structures, previously conditioned at CERN and stored for approximately five years, were successfully reconditioned and tested at Mel-BOX, demonstrating that long-term storage does not significantly degrade high-gradient performance. SLED-I pulse compressors were also reconditioned as high-gradient RF subsystems in standalone operation. One unit was subsequently upgraded with newly designed removable copper tuning plates (cups), enabling improved matching control. High-power loads, installed at the end of the line throughout all campaigns, were exposed to the full RF conditions. They sustained peak power levels of up to 50 MW delivered by the upgraded pulse compressors, demonstrating reliable operation under nominal high-power conditions. These results establish Mel-BOX as a mature X-band platform for high-gradient testing and subsystem integration, supporting the development of compact accelerator systems for medical, industrial, and scientific applications.

INTRODUCTION

The realisation of the CLIC [1] concept requires normal-conducting X-band accelerating structures capable of operating at gradients of 100 MV/m with breakdown rates below 3×10^{-7} per pulse per metre, in order to limit luminosity degradation. Achieving these conditions relies on systematic high-power RF testing to characterise breakdown behaviour and optimise performance.

Mel-BOX [2–6], installed at the University of Melbourne, provides a dedicated high-gradient test platform derived from CERN's XBOX3 infrastructure. The facility delivers 12 GHz pulsed RF using two klystrons combined through SLED Type I pulse compression [7], enabling peak powers of several tens of MW with sub-microsecond pulse lengths at high repetition rates.

The present work extends the experimental programme towards system-level validation, including the reconditioning of stored accelerating structures, standalone operation and optimisation of pulse compressors (PC), and high-power testing of RF loads under nominal conditions.

THE TEST STAND FACILITY

A layout of the final RF network of Mel-BOX configuration is shown in Fig. 1.

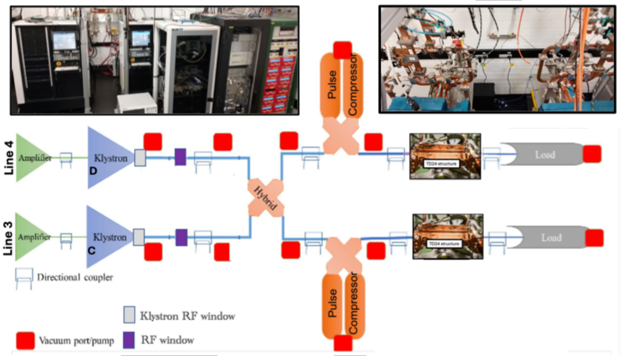

Figure 1: Last Layout of the Test Stand: Two Lines with Two Structures and Pulse Compressors.

Two RF windows (E42170 Canon Electron Tubes & Devices) have been installed between the kylstrons and the rest of the waveguide network [8], Fig. 1, where they provide an extra layer of protection for the klystrons which have a long lead time for replacement, particularly so in Australia.

Klystron RF power is guided into two high-Q cavities after in-phase combination at a hybrid coupler. The cavities then discharge RF power in the forward direction upon a 180° phase reversal, producing a compressed pulse with higher peak power and shorter duration. The cavities are tuned via a removable copper piston. An improved design, developed at CERN, was implemented on Line 3 to mitigate dipole mode effects and reduce breakdown rates. During conditioning of this pulse compressor, each cavity was controlled by a separate chiller, rather than using a single chiller to keep both cavities at the same temperature. Both lines are terminated with ~1m stainless steel RF loads, with directional couplers, pumping ports, and vacuum gates completing the network.

HIGH POWER CONDITIONING

A key advancement in this campaign is the upgrade of the pulse compressors through a new copper cup design applied to the cavity end plates. While the pulse compressors had previously been tested at CERN, the final tuning elements were replaced at Mel-BOX. The upgraded pulse compressor was reconditioned to withstand 50 MW peak power for the first time in Line 3 of Mel-BOX (Fig. 2), which was operated without a structure and terminated with a stainless steel load. The 50 MW milestone highlights that both the modified

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Table 1: Conditioning Summary Table of Components Along the Two Lines

Component	**Pulse [µm]**	**Uncompressed Power [MW]**	**Flat-top (FT) [ns]**	**FT Peak-Power [MW]**	**Rate [Hz]**	**Aver. Power [kW]**
Window C	2.8	6.2	2800	6.2	200	3.5
Window D	2.8	5.5	2800	5.5	200	3.1
Pulse Compressor Line3 Old Cups	2.5	10	80	40	100	3.2
Pulse Compressor Line3 New Cups	2.8	12	80	50	100	3.5
Pulse Compressor Line4	2.5	9.5	80	38	100	3
1-meter-long stainless steel load 3	2.8	12	80	50	100	3.5
1-meter-long stainless steel load 4	2.5	9.5	80	38	100	3
TD24-N1 installed in line 3	2.8	10	80	43	100	2.8
TD24-N2 installed in line 4	2.5	8.5	80	38	100	2.2

pulse compressor and the RF load can sustain high-power operation. This marks a significant step forward for Mel-BOX, as it validates that nominal CLIC parameters can be reached by the system even after substantial modifications to components such as the pulse compressor.

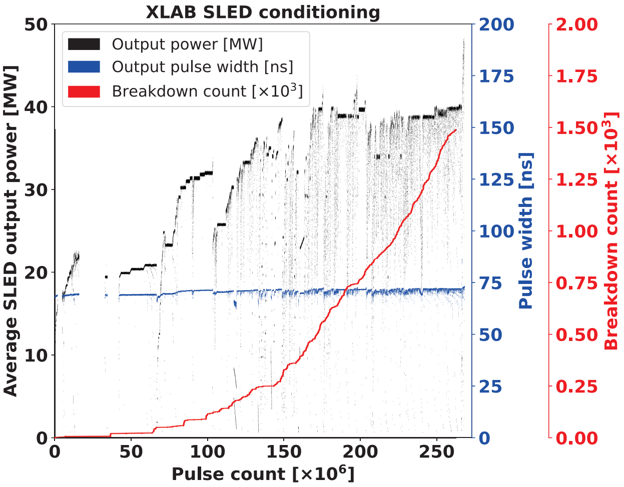

Figure 2: Line 3 Pulse Compressor Conditioning with new Copper Cup Design.

We achieved 50 MW by extending the input pulse to 2.8 µs and increasing the klystron cathode voltage difference (CVD) to 160 kV. In addition, we adjusted the temperature difference between the two cavities to minimise reflections at the pulse compressor, thereby increasing the delivered power. Figure 3 shows the peak and average reflected power as a function of the temperature difference between the first and second cavities for different input power. The PC input energy is shown as well. The top plot corresponds to operation without the accelerating structure, while the bottom plot includes the structure. A small temperature difference (0.5–1 °C) between the SLED cavities detunes the frequency, introducing a phase shift that modifies interference at the hybrid. For example, a temperature offset $\Delta T \sim 0.5$–$1\,^{\circ}$C between the SLED cavities detunes frequency as $\Delta f/f \approx -\alpha \Delta T$ ($\alpha \approx 17 \times 10^{-6}\,\mathrm{K}^{-1}$), i.e. by $\Delta f \sim 100$–200 kHz at 12 GHz. While the presence of a structure increases overall reflections, we observe an identical trend in both with and without the structure: at high power, optimal matching is achieved when the second cavity is slightly warmer, compensating system asymmetries and reducing reflected power.

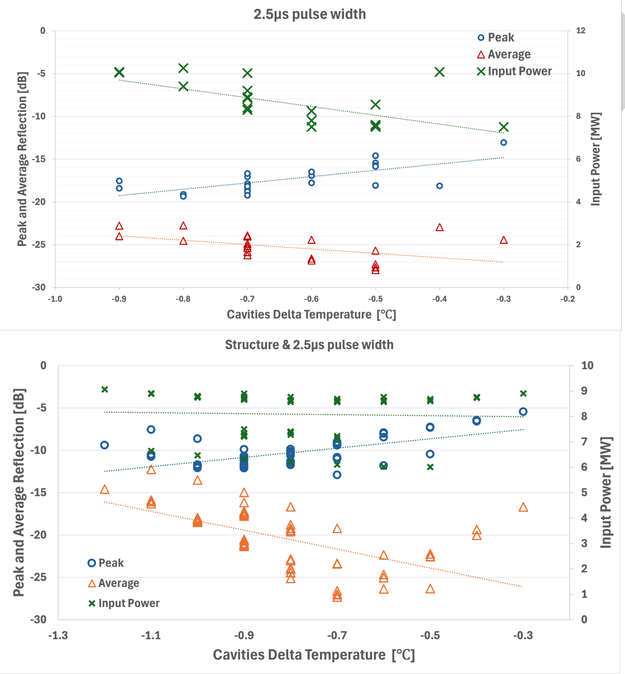

Figure 3: Peak and Average Reflections as a function of the Delta Temperature of the Cavities.

Following standalone PC conditioning, we installed the TD24N1 baked-out structure, to assess impact of long-term storage on structure performance and verify Mel-BOX's operation at nominal CLIC parameters. TD24N1 was conditioned to 100MV/m (~42.2 MW) at CERN in 2019. As demonstrated in Fig. 4, the structure achieved ~43 MW average power at Mel-BOX in 400 million pulses. In this regime, conditioning is clearly dominated by the structure itself, with no observable limitations from the pulse compressor or load. To ensure a reliable comparison between the CERN and X-LAB data, the same breakdown conditioning threshold of 5×10^{-5} per pulse per metre was used. The same pulse compressor conditioning threshold was also applied.

In Fig. 5, the conditioning performance of TD24N1 at CERN and X-LAB is compared, showing that the structure recovered its original performance nearly four times faster at X-LAB than during the CERN conditioning campaign. Un-

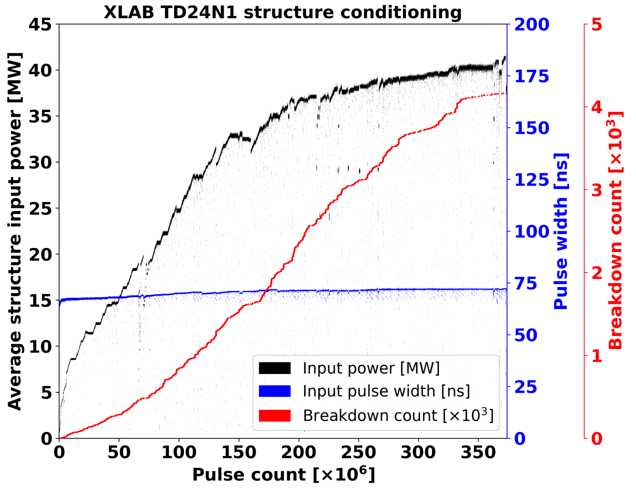

Figure 4: TD24N1 Baked-out Structure Conditioning.

fortunately the power was limited to 43 MW by degradation of one klystron cathode, reducing its output to below 5 MW. With forward power of both klystrons ganged in-phase at the hybrid coupler, the power-limited klystron constrains summed power.

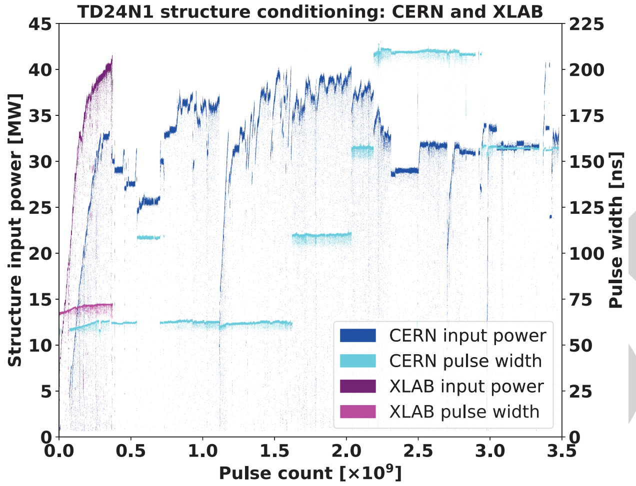

Figure 5: TD24N1 Baked-out Structure Conditioning at CERN and X-LAB.

The unbaked TD24N2 structure (Fig. 6) did not reach the 42.2 MW achieved at CERN, currently limited to a maximum of 38 MW by breakdowns originating mainly within the structure. Notably, this level was achieved with approximately half the number of pulses required during the CERN campaign, again indicating a significantly faster conditioning process despite the lower ultimate gradient. The gap in TD24N2 conditioning progress at CERN at 1.4 $\times 10^9$ pulses (indicated in blue in Fig. 6) is due to chiller malfunction on Line 4 of the CERN XBOX3 test stand in November 2018.

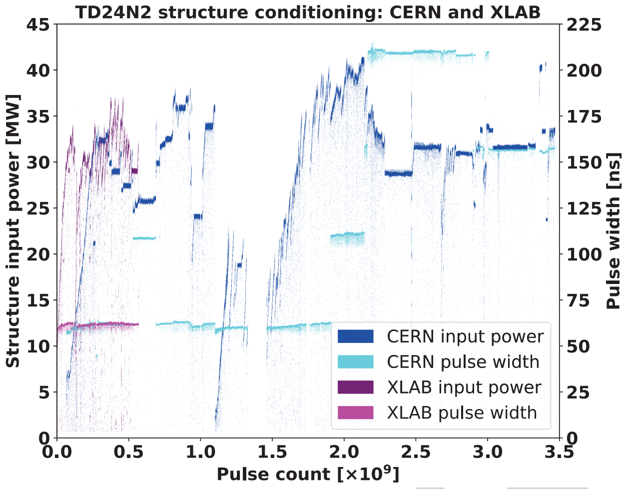

Figure 6: TD24N2 No Baked-out Structure Conditioning at CERN and X-LAB.

Table 1 summarizes the conditioning results of components tested in Melbourne on the last years. It reports peak uncompressed and flat-top power levels, along with their pulse widths. The final rows reflects the two TD24 structure conditioning results. The new piston pulse compressor is also included. Note that the loads and pulse compressors value are refer to theocnditioing without the structures installed on the lines, that means the loads is seeng all the power directly from the PCs.

CONCLUSION

X-LAB has demonstrated stable 50 MW peak power operation with upgraded SLED-I pulse compressors and reliable high-power loads. The TD24-N1 structure was successfully reconditioned to nominal performance, reaching ~43 MW with a conditioning time nearly four times shorter than at CERN, while TD24-N2 reached 38 MW, limited by intrinsic breakdowns. These results confirm the maturity and competitiveness of the facility, showing that long-term storage does not significantly degrade high-gradient performance. The standalone optimisation of the pulse compressors further highlights the capability of Mel-BOX as a flexible X-band platform for high-gradient testing, RF subsystem qualification, and integrated accelerator R&D.

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