High-Efficiency Klystron Tests at the CERN Xbox3 Facility

Author: Maggie Webber
Supervisors: Paz Alonso Arias , Chiara Marrelli (SY-RF-MKS)

CERN Summer Student Report
23 August 2024

Abstract

Klystrons are a type of radio-frequency amplifier widely used in high-energy physics. In recent years, efforts have been made to improve klystron efficiency to reduce power consumption. This report details the adjustments made at the CERN Xbox3 X-band test stand to facilitate the testing of high-efficiency klystrons. We present measurements of the output power, gain, and spectral composition for an E37117 klystron developed in collaboration with Canon Electron Tubes and Devices under the high-efficiency klystron programme at CERN. This prototype is designed to produce a peak output power of 8 MW, however our results show that the klystron significantly underperforms, producing only around 5 MW. Although it may not fully resolve the discrepancy, for future measurements we have installed a new load to dissipate the klystron output power that has a better impedance match with the line. As well as improving the reflected power and vacuum levels in the line, this may have an effect on the klystron output power. Finally, we discuss the challenges involved in implementing calorimetric measurements to provide an independent measurement of the average output power of the klystron.

1 Introduction

The high-efficiency klystron programme at CERN was established to study the factors that limit the efficiency of klystrons, a type of radio frequency (RF) amplifier. In collaboration with industry partners, this has led to the development of a series of high-efficiency klystron prototypes.

The operating principle of a klystron (Fig. 1) is based on an electron beam that passes through a series of resonant cavities [1]. At the input cavity, the RF field due to the input signal modulates the velocity of the electrons, resulting in a bunched electron beam. In the output cavity, the electron beam is decelerated and the RF signal, amplified by the energy of the beam, is extracted. Additional cavities can be used to improve the bunching of the beam, the bandwidth of the klystron, or to control higher order harmonics in the beam.

Klystron technology is mature, and has been in use throughout the decades since the first prototypes were built in 1937. Klystrons are widely used in high-energy physics, providing RF power to accelerating cavities for particle accelerators. They also have numerous applications in high-energy communications. The efficiency of pulsed, high frequency, and high peak power klystrons has generally been limited to at most 45% [2]. One of the key factors limiting klystron efficiency is the bunching of the electron beam. Poorly bunched electrons result in less power extracted at the output cavity, because the electrons passing through the cavity do not have the expected velocity. Under the high-efficiency klystron programme at CERN, new bunching techniques have been developed following in-depth studies using new computer simulations and beam dynamics.

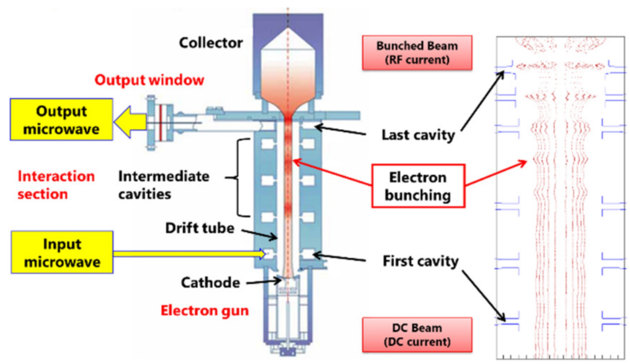


Figure 1: Schematic of a typical klystron. The electron beam is generated at the cathode, passes through the drift tube, and is absorbed by the collector. The right image shows the beam density along the tube, demonstrating the bunching of the beam. Figure reproduced from [2].

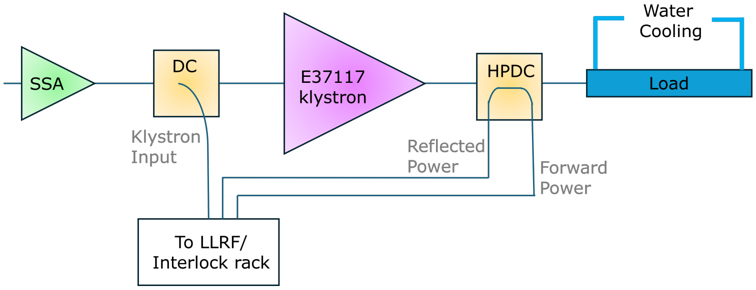
The Xbox3 facility at CERN consists of two klystron-modulator systems that are combined to provide high peak power at short pulse lengths. The facility was built to test and condition high-gradient accelerating structures and other high-power RF components designed for the Compact Linear Collider (CLIC) project. CLIC is a proposed electron-positron collider that is currently under development at CERN. It is planned to operate at three successive stages, at centre-of-mass energies $\sqrt{s} = 350$ GeV, 1.4 TeV, and 3 TeV. CLIC would enable precision measurements of processes described in the Standard Model, as well as exploring physics beyond the Standard Model. It would allow for a wide range of phenomena to be studied, most notably Higgs boson and top quark physics [3, 4]. To reduce the length of the accelerator, high gradient accelerating structures are required. The performance target for CLIC accelerating structures is a gradient of 100 MV/m, with a maximum breakdown rate of 3×10^{-7}/pulse/m. The structures are supplied with RF power at a frequency of 11.994 GHz. The design and testing of these structures has been ongoing for several years, and the Xbox3 X-band test stand has been instrumental for performing such tests.

Currently installed at the Xbox3 facility is an E37117 klystron manufactured by Canon Electron Tubes and Devices (Canon ETD). This klystron was designed using a retrofit approach, based on the previous E37113 model. According to the design specifications and test results reported by Canon ETD, the E37117 prototype produces 8 MW peak output power with 56% efficiency at 11.994 GHz. This is a significant improvement over the E37113 model, which can produce 6 MW peak output power at only 39% efficiency. The aim of my project was to characterise the E37117 klystron, to verify the new high-efficiency klystron technology.

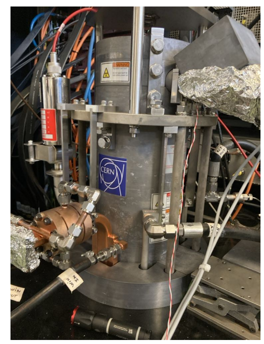
2 Adapting the Xbox3 test stand for klystron tests

The Xbox3 facility at CERN was originally designed for the conditioning and testing of accelerating structures. Several modifications to the setup, controls, and data acquisition were made to facilitate klystron testing.

Figure 2 shows the setup used for klystron tests. The low-level RF (LLRF) system consists of an NI PXI crate responsible for up- and down-mixing signals to the correct frequency. The initial, low power RF signal is generated by the PXI system and preamplified by a solid state amplifier (SSA) before reaching the klystron. The klystron output power is dissipated by an X-band high power load. The vacuum level in the line is maintained at approx. 10^{-8} mbar by an ion pump. Directional couplers allow for the forward and reflected power to be measured at the input and output of the klystron. The forward power signal is sent to the PXI acquisition system, while the reflected power signal is sent via a log detector to the interlock system, which prevents too much power reflecting towards the klystron.



(a) Diagram of setup for klystron tests. A directional coupler (DC) and high power directional coupler (HPDC) are used to measure power at the input and output of the klystron, respectively.



(b) Canon ETD E37113 high-efficiency klystron

Figure 2: Setup for klystron tests

2.1 Acquisition

A modified version of the LabVIEW code used to control data acquisition at the Xbox3 facility was developed specifically for klystron tests. Several acquisition channels that were no longer necessary were removed, including those corresponding to the accelerating structure under test and other components further down the line from the klystron.

The klystrons are pulsed at up to 400 Hz. Recording every single pulse is unrealistic due to the time and computing resources required to process the amount of data generated. Instead, one pulse is recorded every 1 ms. In addition, three pulses are logged every time a breakdown event is detected (including the breakdown pulse, and the two previous pulses). This can provide information about the breakdown event, which is useful for testing accelerating structures.

A major change to the acquisition system was the addition of channels to record the beam current and beam voltage of the klystron. These parameters are related to the current and voltage supplied to the cathode where the electron beam is produced. The output power of the klystron is sensitive to the beam current and voltage because these affect the energy of the electron beam. For conditioning and testing accelerating structures, small variations in beam current and voltage are less important than the overall long-time behaviour, and it was sufficient to measure these parameters manually using an oscilloscope when needed. However, to understand klystron performance, in particular for measuring the efficiency, we would like to record this information on a pulse-by-pulse basis to see the effect on the output power. Accordingly, an NI PXIe-5162 oscilloscope module was added to acquire the beam current and voltage. The new channels were added to the existing acquisition system, so they are saved with the rest of the data and can be displayed in real time on the user interface.

A challenge that we encountered is that the acquisition period of the system is shorter than the beam current and beam voltage pulse length, so we cannot capture the entire pulse without changing the acquisition length for every other variable. Since this measurement is not critical for most purposes, this is left for future work. For most purposes, we only need to measure the magnitude of the current and voltage at the flat top of the pulse. A measurement of the full pulse shape is only required if we need to know the total power (integrated over the pulse), which is important for calorimetry (discussed in Section 5). Instead, we can take advantage of the fact that the pulse shape remains consistent from pulse to pulse over a long time period. This means that we can record the pulse shape using the oscilloscope and then scale it using the average value of the flat-top peak.

2.2 Interlocking

The Xbox3 interlock system is designed to protect components of the system and allow it to operate safely. The important interlocks are vacuum (if the pressure in the line is too high, sparks occur more frequently) and reflected power (which can travel back to the klystron, damaging it).

The NexTorr vacuum modules send an interlock signal to the PXI to switch off the input RF signal, and also a separate interlock signal to the modulator to stop the klystron pulses from triggering.
In the original Xbox3 setup, there are several vacuum modules corresponding to various points along the system (after the klystron, at the structure currently under test, at the load etc.) that are connected in series. This means that the vacuum interlock trips unless every vacuum reading is under threshold.

For the klystron measurements, the vacuum pumps further along the line are disconnected. To adapt the interlock system to the new configuration, the interlock signals of the unused vacuum modules were manually bypassed by adding jumpers at the back of each mode to make the signals appear as if the interlock switch inside the module was closed.

2.3 Data Processing Code

A new `python` code was developed for processing the data recorded. The data is recorded in two separate NI TDMS files. The 'event' file records pulse information, including the beam current and voltage supplied to the klystron, and the input and output power measured for each pulse; while the 'trend' file contains parameters recorded to observe long-term trends such as vacuum levels, temperatures, and the klystron operating frequency. The code reads in data from both of these files and merges them based on the timestamp of each pulse. For pulse measurements, the pulse length, the integrated pulse, and the average of the flat-top of the pulse are calculated. The raw data from each channel is also multiplied by scaling coefficients that calibrate the raw ADC counts to the correct measurement value.

The most time consuming part of the process is reading the NI TDMS files. After the data is extracted and processed, it is written to a HDF file. This file format is much more quickly accessible, and means that the time costly process of reading the NI TDMS file only needs to be performed once. The data is stored on a day-by-day basis, with a key corresponding to the date. This means that the user can specify a range of dates, and the code can look up the data corresponding to those dates in the hdf file. Only if data corresponding to a particular date is not already stored in the hdf file does the code turn to extracting data from the original NI TDMS files.

3 Measurements

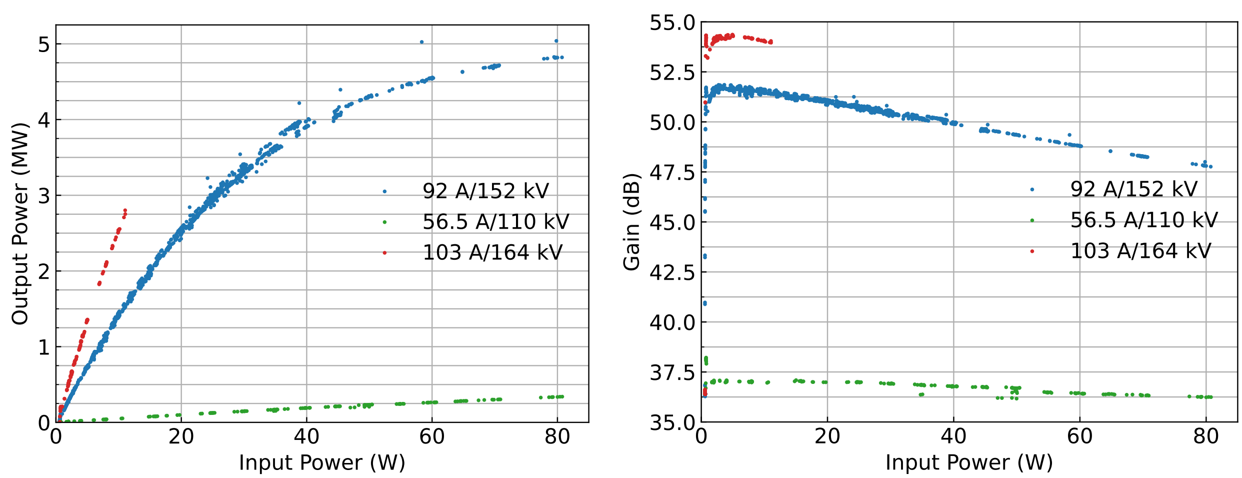
3.1 Gain Curve

The first measurement we performed was a measurement of the klystron gain. Figure 3a shows the gain curve of the klystron at the nominal operating point of 93 A/153 kV in blue. The width of the curve is due to variation in beam current. The maximum input power that we were able to deliver to the klystron was 80 W, beyond which the vacuum and reflected power levels became too high. Although the gain curve does not quite reach saturation, it is clear that the power output is barely reaching 5 MW, far below the 8 MW reported by Canon ETD.

To confirm that the klystron is operating at the correct operating point, a further two gain curve measurements were taken (Fig. 3) with beam current/voltage both higher (shown in red) and lower (shown in green) than the nominal operating point. For the high beam current measurement, the maximum input power that could be reached while maintaining vacuum levels was around 15 W. Consequently, the output power is clearly not near saturation. The gain is around 53 dB. The output power remains below 1 MW for the operating point at lower beam current. Here, the gain is around 36–37 dB. At this operating point, it was also not possible to reach saturation of the output power due to limitations on the input power that could be generated.

Although these measurements were not taken at saturated output power, they can still be used to compare the behaviour of the klystron at different setpoints. The measured gain is reasonable when compared to the saturated output characteristics recorded by Canon ETD (shown in Fig. 4). At 160 kV, the gain is around 46 dB. Although the measured gain was around 53 dB, this is far before the saturation point so this is entirely possible. At 110 kV, the saturated output corresponds to a gain of 35 dB, so our measurement of 36–37 dB before saturation is reasonable. Most importantly, this correspondence between our measurement and the saturated output characteristics reported by Canon ETD shows that the operating point of the klystron is accurate. The unexpectedly low power output cannot be attributed to the klystron beam current being incorrect.

Another factor that can significantly affect the output power is the frequency of the RF signal. We confirmed that the klystron was operating at the expected centre frequency, 11.994 GHz, using a signal analyser to measure the input signal.



(a) Gain Curve

(b) Gain vs input power

Figure 3: Klystron performance at different beam current/voltage setpoints. The nominal operating point is 93 A/153 kV, shown in blue.

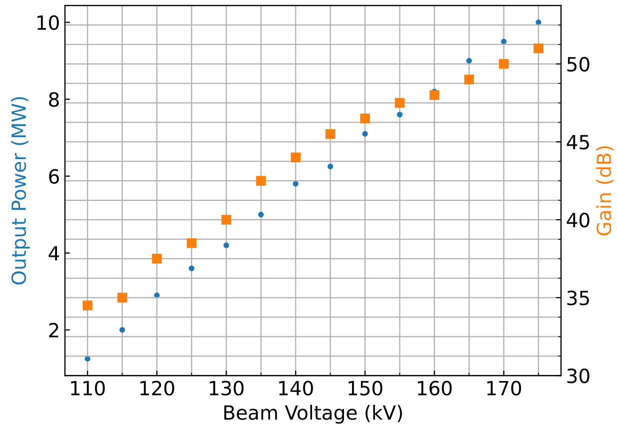


Figure 4: Saturated output characteristics reported by Canon ETD.

Having determined that the klystron was operating at the nominal frequency and current setpoint, we also double checked the calibration that accounts for the attenuation of the output coupler and the cables that carry signals to the PXI. Prior to the measurement, the attenuation of each cable was measured. To do this, a signal generator was used to produce a signal with known amplitude that was passed through each cable. The attenuation of the signal could then be measured using a power meter. The attenuation of the output coupler was measured using a two-port vector network analyser (VNA). This was done after the measurement, because disconnecting the output coupler requires breaking the vacuum. The measured attenuation of the output coupler matched previous measurements, so this confirms that the power measurements are correct.

While the cause of the discrepancy between our measurements is not yet clear, the history of the klystron under test should be taken into account. During the first testing stage of the E37117 klystron, it was found to present instabilities in the shape of the pulse. Additionally, it was found to produce components at 20 GHz frequency, below the second harmonic. After these observations, the klystron tube was modified to remove these issues before it was installed at Xbox3 for our measurements. Although these modifications should be successful, it is worth noting that issues have been observed in the past.

Throughout the measurements, spikes in the vacuum occurred frequently and the reflected power measured in the line was also unusually high. The impedance of the load used to dissipate the klystron output power was measured using the VNA. We found that the load was not a good match to the klystron output impedance. This explains why the reflected power level was unusually high. Crucially, a mismatched load could affect the output power of the klystron, because the interference between the incident and reflected signals will change. This may not fully explain the discrepancy between the expected output power and our measurements, but it needs to be investigated further. A different load with better return loss has been installed in the line for future measurements. The new load will provide a more accurate picture of the klystron performance.

3.2 Spectrum analysis of klystron output

Measuring the spectrum of frequencies contained in the klystron output is of interest because indicator of instabilities because the klystron is designed to amplify only frequencies near 11.994 GHz. It may also shed light on the output power measured, because the signal acquired by the PXI is filtered so that the power is measured only at the fundamental frequency, 11.994 GHz. The presence of higher order modes at different frequencies would indicate that the klystron is not performing as expected, perhaps due to manufacturing errors.

A spectrum analyser connected to the klystron output was used to measure the spectral content, shown in Fig. 5. The main peak is at the nominal operating frequency, 11.994 GHz. The second harmonic at 23.988 GHz can also be seen, with an amplitude around 12 dB smaller. However, it must be noted that the amplitude measured by the signal analyser may not accurately reflect the klystron output. The response of the directional coupler connected to the klystron output depends on frequency, so it may be different at the second harmonic. Unfortunately, we cannot measure the response of the directional coupler at this frequency because we currently do not have the equipment to calibrate the VNA above 12 GHz. Furthermore, the response of the directional coupler will be different for different modes at the same frequency. There is no way to know which modes are excited in the waveguide— the behaviour of three higher order modes have been modelled based on the geometry of the klystron and waveguides, but this may not correspond to the physical prototype. Consequently, the second harmonic may well be within the expected level.

Although comparing the amplitude of different modes is difficult, spectral measurements can still provide important information about the klystron behaviour. A future measurement should be performed to examine the klystron output at frequencies near 20 GHz, since before the tube was fixed the klystron had previously produced unusually high components in this region (see section 3.1).

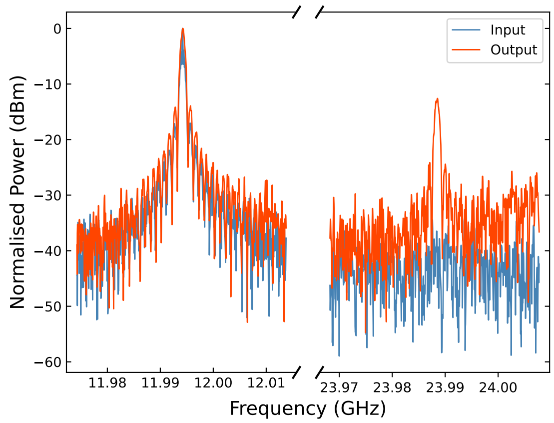


Figure 5: Spectral measurements of the klystron output (red). The input signal is shown in blue for comparison. The main peak at the operating frequency of 11.994 GHz and a smaller component at the second harmonic 23.988 GHz are visible. The measurements are normalised to the maximum power for the input and output respectively.

3.3 Calorimetry

In addition to measuring the output power by digitising the signal from the high power directional coupler, we have implemented temperature probes in the cooling system to perform calorimetry measurements of the power dissipated in the load. Calorimetry has been shown to provide an accurate and independent power measurement [5]. Crucially, the calorimetry measurement does not depend on the modes excited in the waveguides. This will allow us to confirm the performance of the klystron and, in combination with the power measurements from the directional coupler, evaluate the impact of different higher order modes.

Two PT1000 resistance temperature detectors (RTDs) are installed at the inlet and outlet of the water cooling in the load. The water flow rate is recorded by a flowmeter at the outlet. The power absorbed by the water cooling system is

$$P = c\dot{m}\Delta T, \tag{1}$$

where ΔT is the temperature difference between the water inlet and outlet, $\dot{m}$ is the water flow rate, and $c = 4186$ J·kg^{-1}°C^{-1} is the specific heat capacity of water at 30°C.

For an accurate power measurement, the temperature difference ΔT needs to be at least 1°C. The minimum flow rate that can be delivered by the cooling system is $\dot{m} = 3.8$ l/min. Since the klystron output is pulsed, the average power delivered to the load is determined by the peak power P_{peak}, the pulse length T_p (nominally 1 μs), and the pulse repetition rate PRR (up to 400 Hz). For example, for a peak power of 1 MW and repetition rate of 200 Hz, the average power delivered is

$$P = P_{\text{peak}} \cdot T_p \cdot \text{PRR} = 200 \text{ W} \tag{2}$$

At the minimum flow rate, this would produce a temperature difference of only $\Delta T = 0.75$°C. Consequently, to perform accurate calorimetry measurements we need to operate at high repetition rate, ideally at the maximum of 400 Hz. However, higher repetition rates cause more load on the vacuum. Due to vacuum issues, the system was unable to run at these high repetition rates. With the load replaced to improve the impedance match with the line, the vacuum should be more stable for future measurements.

4 Conclusion

We present the first measurements for characterising the output power, gain, and spectral components of a new high-efficiency klystron prototype developed by Canon ETD in collaboration with CERN. Several adaptations were made to the setup and acquisition system at the Xbox3 X-band test facility at CERN to perform these tests. The measurements showed that the klystron did not perform to specification, with the peak output power saturating close to 5 MW rather than the 8 MW it is designed to produce. Several challenges were involved in the measurement, most notably poor vacuum levels and unexpectedly large reflected power in the line. For future measurements, the load used to dissipate the klystron output power has been replaced with one with a better impedance match. This is essential because the poor impedance match of the original load used for the measurements may affect the output power of the klystron. Additionally, a better impedance match should reduce the level of reflected power and improve the vacuum. With vaccuum and reflected power levels improved, we expect to be able to operate at a higher repetition rate of 400 Hz which will allow for calorimetry to provide an independent measure of the klystron output power.

5 Acknowledgements

I would like to thank my supervisors Paz and Chiara for sharing their expertise and for their support and patience. Thanks also to Matt Jones and to the rest of the MKS section for welcoming me.
Finally, a huge thank you to Matteo Volpi, Suzie Sheehy, and Paul Giansiracusa, without whom this incredible opportunity would never have become a reality.

References

[1] A. S. Gilmour, *Klystrons, traveling wave tubes, magnetrons, crossed-field amplifiers, and gyrotrons*, Artech House microwave library (Artech House, Boston, Mass., 2011).

[2] Catalan-Lasheras,Nuria, Beunas,Armel, Burt,Graeme, Syratchev,Igor, et al., "High-efficiency klystrons from a dream to a reality", in (2024), pp. 3933–3938.

[3] H. Abramowicz, A. Abusleme, K. Afanaciev, N. Alipour Tehrani, et al., "Higgs physics at the CLIC electron–positron linear collider", The European Physical Journal C **77**, 475 (2017).

[4] H. Abramowicz, N. Alipour Tehrani, D. Arominski, Y. Benhammou, et al., "Top-quark physics at the CLIC electron-positron linear collider", Journal of High Energy Physics **2019**, 3 (2019).

[5] N. C. Lasheras, C. Eymin, G. McMonagle, S. Rey, et al., "Commissioning of XBOX3: a very high capacity X-band RF test stand", in Proceedings of LINAC2016, East Lansing, MI, USA (2017).