VALIDATION OF HIGH EFFICIENCY KLYSTRON TECHNOLOGY

P. Alonso-Arias*, N. Catalán-Lasheras, A. Chauchet, S. González-Antón, C. Marrelli,
I. Syratchev, Z. Un-Nisa, M. Webber, CERN, Geneva, Switzerland
M. D. Jones, ASTec STFC Daresbury Laboratory and Cockcroft Institute,
Sci-Tech Daresbury, Warrington, U.K.
M. Boronat, IFIC (UV-CSIC), Valencia, Spain
T. Anno, Canon ETD, Otawara, Japan

Abstract

The delivery of high RF power—from hundreds of kW to MW—by klystrons, is linked with a high overall energy consumption. A research programme led by CERN in collaboration with the industry is being conducted to understand what limits klystron efficiency and how to develop high-efficiency klystrons. As a result of this program, two first prototypes of X-band (11.994 GHz) high-efficiency klystrons have been successfully designed and manufactured in collaboration with Canon Electron Tubes and Devices. The first results look promising, revealing a remarkable 56 % efficiency, and validating the proposed HE klystron technology. A comprehensive characterisation campaign has been conducted at CERN to verify and demonstrate these results. The methodology for the HEK tubes characterisation is based in two independent measurements: a RF power measurement, and a calorimetric methodology—less subject to calibration inaccuracies. We describe the setups, principle of the calorimetry methodology, and we discuss the feasibility and precision of the results.

INTRODUCTION: AN X-BAND HIGH-EFFICIENCY KLYSTRON

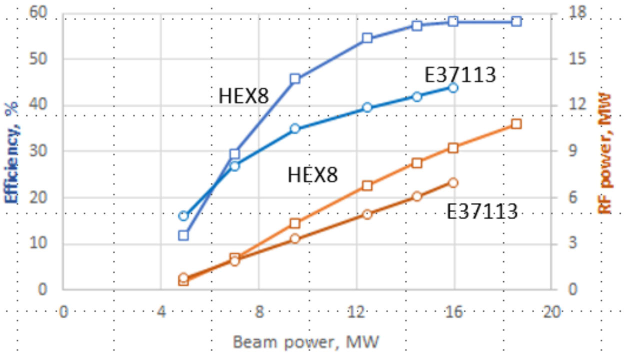

Figure 1: Expected performance of the E37117 tube (HEX8) built by CANON ETD in collaboration with CERN in comparison with the original model E37113.

The new high efficiency tube E37117 uses a retrofit approach from the original Canon E37113 model. The original model, used for years at CERN Xboxes facilities, delivered a maximum power of 6 MW for a 5 s pulse and 400 Hz repetition rate. Canon ETD delivered two new prototypes following the design provided by CERN, which maintained the electron gun and the collector, and introduced a six-cavity bunching circuit followed by a three-cell output cavity [1]. In addition, the tubes include a new ceramic window presenting lower surface electrical fields—result of a previous collaboration between CERN and Canon ETD—, which allows higher peak powers. In Fig. 1 and Table 1, we present the expected performance of the new klystrons in comparison with the original model.

Table 1: Performance Metrics of the X-band Klystron Tubes Manufactured by Canon ETD for CERN

	E37113	E37117
Beam voltage, kV	157	153
Beam current, A	96	93
Peak output power, MW	6	8
Efficiency	39	56

TEST STAND FOR X-BAND HEK AT CERN

The two prototypes have been installed for their testing in the Xbox3 klystron-modulator system at CERN. Xbox3 is used to evaluate and test high-gradient accelerating structures and high-power RF components in the context of the Compact Linear Collider (CLIC) project [2].

The system consists of a Scandinova 170 kV modulator system that delivers the pulsed power to the klystron cathode, waveguide network for the distribution of the RF power, pulse compressor, and auxiliary power supplies and dedicated subsystems for control, interlocking, and diagnosis. Originally, Xbox3 was designed for conditioning structures rather than testing klystrons. Consequently, the test stand has been modified for the current measurement campaign. These modifications include the addition of new channels to acquire the high-voltage pulses from the modulator, as well as signals necessary for calorimetry. These improvements enable effective measurements of the klystrons performance in a reliable and secure testing environment.

For the klystron commissioning, an assembly consisting of a X-band high power load is connected to the klystron output. At the end of the transmission line, an ion pump has been integrated to maintain vacuum levels of approx. 10^{-8} mbar.

Two directional couplers (regular, DC, and high power, HPDC) allow the measurement of the klystron's input and

---

[*] paz.alonso.arias@cern.ch

output power, as well as the reflected power towards the klystron, which is directed to the log-detectors in the interlock rack. This configuration ensures accurate monitoring of the klystron's performance and helps in managing any reflected power that could potentially affect the system. The signal of each channel is digitised by the PXI acquisition system, and is also accessible through a power meter installed in the LLRF rack. The different lines have been carefully calibrated to minimise measurement uncertainty.

CHARACTERISATION OF THE HE TUBES

We first determined the operating point of the klystron cathode, searching for the perveance knee when varying the filament current. The optimal point for the E37117 tubes is at 9.5 A.The selected operational point is consistent with the specifications provided by Canon. The two tubes have been characterised with 1 s-pulsed signals up to 400 Hz repetition rate.

Transfer Characteristics

The E37117 tubes are designed to operate at a nominal beam voltage of 154 kV. The transfer characteristics of the HE tubes were measured at different levels of beam voltage. For this purpose, we first adjusted the beam current, taking as a reference the microperveance ($P = (I/V^{3/2}) \times 10^6 = 1.55$) specified by design, and confirmed by Canon. This approach was followed because the capacitive voltage divider (CVD) installed in the tank does not provide the required precision (approx. ±8 %), and we observed discrepancies of up to 15 % compared to the expected value. The transfer characteristics were then measured for several beam voltages, progressively increasing the drive power until the klystron reached saturation.

Figure 2 presents the klystron performance (saturated output, gain) for the first prototype (22M001), in comparison with the measurements reported by the manufacturer. Efficiency, as measured by Canon ETD, is 56 % at nominal beam voltage. Although we have not been able to measure the efficiency at CERN with the required accuracy, the results in terms of gain and output power confirm Canon's results. In addition, we studied the performance of the tube at different magnetic fields, as shown in Fig. 3. The results show that we can slightly increase delivered power and efficiency by optimising beam size, matching simulations results (higher values of main coil and counter coil currents reduce oscillations). Frequency measurements revealed that the central frequency is shifted by −20 MHz from the 11.994 GHz, a deviation that was already known and had been confirmed by Canon.

We encountered unexpected results when measuring the second prototype, regarding the maximum delivered power. The characteristics of the tube are very similar to those reported by Canon, but the output power saturates before reaching the expected 8 MW. We have found that the installed HP load did not present a good match to the line. As this mismatch may be reducing the power output, the load has been replaced by one with better return loss. We expect these changes to improve the results, since after checking RF calibration, calorimetry and operational point, this issue remains unresolved.

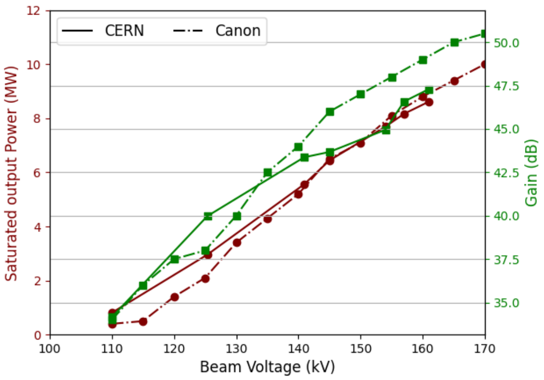

Figure 2: Saturated output characteristics for the first tube E37117 22M001.

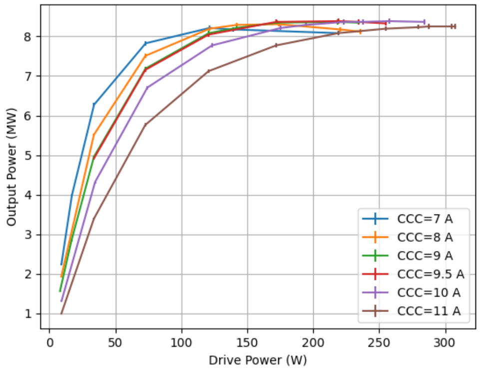

Figure 3: Transfer characteristics versus beam size in the tube E37117. For these measurement, counter coil current (CCC) has been varied while maintaining a main coil current of 32 A.

Measurement of Harmonics

Due to the surprising results obtained for the second prototype, the spectral content of the klystron output signal was measured with a signal analyser. Two two hypotheses have been considered: first, that instabilities may be arising from unwanted components around 20 GHz, as similar issues were encountered earlier in the klystron's development [3]. However, we do not observe instabilities; instead, the pulse exhibits a correct and flat profile.

Secondly, that a high second harmonic generated by the klystron could negatively impact its performance. Figure 4 compares the spectral content of the drive signal with the output. At the coupled port, we find a second harmonic 12 dB below the level of the fundamental. However, considering that the coupling factor of the fundamental and the first two higher order modes (HOM2 and HOM3) differ by approx.

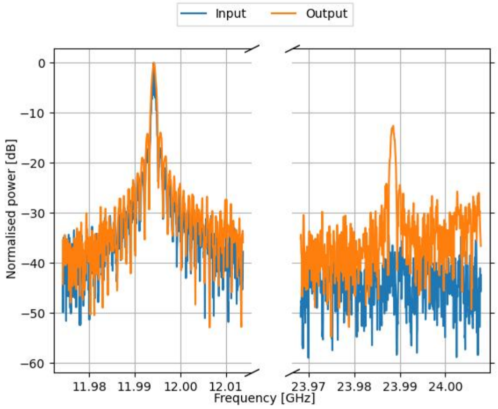

Figure 4: Comparison of the spectral content of the RF signal at the input and output of the klystron amplifier. Results are normalised to maximum power at the fundamental frequency.

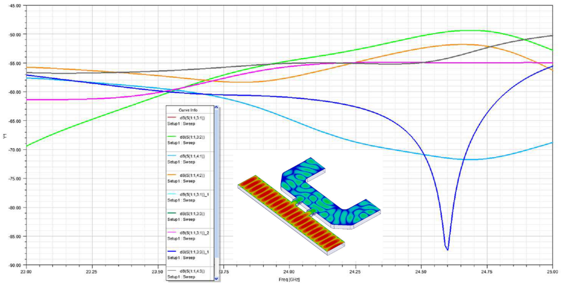

Figure 5: Simulation results of the HPDC performance at 24 GHz, when two HOM are excited in the input port [4].

10 dB, (see Fig. 5), we cannot absolutely confirm that the presence of these modes is affecting the performance of the klystron.

Calorimetry Measurements

In view of the results obtained for the second prototype, we have implemented a setup to measure RF power based on calorimetry, which has been proven to be a very accurate, independent, measurement of power [5]. The RF power coming out of the klystron is dissipated by the RF loads in the form of heat, which is then taken away by the coolant system in the load. The calorimetric setup measures the temperature rise in the coolant, which ideally corresponds to the RF input signal.

The average power passing though the load generates a measurable increase of temperature

$$P = c\dot{m}\Delta T, \qquad (1)$$

where $\dot{m}$ (l/s) represents the water flow rate, T is the difference of the output and input water temperatures, and c is the specific heat of water (the cooling liquid). At 30 °C, c is 4186 J/kg°C.

High accuracy platinum RTDs (PT1000) are used to measure temperature in the RF loads' inlet and outlet tubes. In addition, a flowmeter has been attached at the output of the load. To avoid heat transfer to the ambient environment, we have limited thermal paths between the cooling system and the ambient using heat insulation jackets.

So far, we have encountered some discrepancies between RF and calorimetry measurements, largely because calorimetry is particularly challenging with low duty cycles. However, this approach holds great promise as it will provide independent information about the RF power reaching the load, regardless of the propagated HO modes. This data will be crucial for our understanding of the klystron behaviour and ensuring the accuracy of our results.

CONCLUSION

The new HE klystrons provide a maximum RF output power of 8 MW, and efficiency at saturation of 56 %, as reported by Canon ETD. The results obtained at CERN show a discrepancy with Canon results for one of the tubes (22G002 tube), but validate the design for the other.

Additional efforts are being made to improve the uncertainty of measurement. In particular, we plan to improve the measurement of the beam voltage. We are currently exploring the possibility of installing a more precise CVD in the tank. In collaboration with Scandinova, we are designing a load that simulates the klystron volume, which will enable a more accurate voltage calibration. These improvements will allow us to obtain more precise values for the beam voltage, and consequently better estimates of the perveance and efficiency. Next steps also include the improvement of the calorimetry setup, so that RF and calorimetry measurements are consistent.

Despite the addressed challenges, the campaign has provided valuable insights into the performance of the new HE klystrons, and the planned improvements should enhance the accuracy of future measurements.

REFERENCES

[1] J. Cai and I. Syratchev, "Design Study of X-band High Efficiency Klystrons for CLIC", in *2020 IEEE 21st Int. Conf. on Vacuum Electronics (IVEC)*, Monterey, CA, USA, Oct. 2020, pp. 121-122. `doi:10.1109/ivec45766.2020.9520585.`

[2] N. Catalan-Lasheras *et al.*, "Commissioning of XBox-3: A Very High Capacity X-band Test Stand", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 568–571. `doi:10.18429/JACoW-LINAC2016-TUPLR047`

[3] I. Syratchev, Z. un Nisa, J. Cai, G. Burt, and T. Anno, "DC Beam Stability Issues in the First Commercial Prototype of a High Efficiency 8MW X-band klystron", CERN, Geneva, Switzerland, CERN Report CERN-ACC-2022-0007, CLIC-Note-1176, 2022. `https://cds.cern.ch/record/2812566`

[4] I. Syratchev, private communication, Aug. 2024.

[5] X. Wu, N. Catalán Lasheras, B. Woolley, W. Wuensch, H. Chen, and L. Zhang, "Calorimetric Power Measurements in X-band High Power RF", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2967–2969. `doi:10.18429/JACoW-IPAC2015-WEPMN019`