15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRYD1

HIGH-EFFICIENCY KLYSTRONS FROM A DREAM TO A REALITY

N. Catalan Lasheras†, I. Syratchev, Z. Un Nisa, P. Alonso Arias, C. Marrelli, O. Brunner, CERN, Geneva, Switzerland
A. Baig, G. Burt, University of Lancaster
J. Cai, University of Electronic Science and Technology of China, Chengdu, China
T. Anno, CETD, Otawara, Japan
A. Beunas, K. Haj Khlifa THALES, Vélizy-Villacoublay, France

Abstract

During the past decade a comprehensive R&D program on high-efficiency klystrons has been carried out in collaboration with industry. The first prototypes are being tested and experimental results are promising. After a brief introduction to the activity, we will describe the main results of this R&D focusing on the experimental ones. The next steps and plans using novel topologies for the future colliders will also be introduced.

INTRODUCTION

Since the first prototype built by the Varian brothers in 1937, klystron RF amplifiers have been used in particle accelerators and telecommunication, providing reliable and cost-effective solution. For decades, this technology was considered as a mature one in terms of delivering RF power production efficiency. In general, klystron efficiency in the pulsed, high frequency and high peak RF power tubes was settled at about 42 - 45 %. Moving to moderate power levels, low frequency, CW devices, efficiency of 60 % is a common value in commercial tubes, with a record efficiency of 70 % demonstrated in a few prototypes [1].

In 2015, extensive studies of the klystron technologies were established at CERN in an attempt to increase klystrons efficiency. This activity included development of new computer simulation tools and in-depth studies of beam dynamics to understand the limiting factors. As a result, a number of new methods for beam bunching were developed, that allowed increasing the klystron's RF power production efficiency by 10 % to 30 %, compared to exiting commercial tubes. Under the CERN high efficiency (HE) klystron programme, two such klystrons have been produced or are being prototyped with industrial partners: an 8 MW, pulsed X-band klystron in collaboration with Canon ETD (Japan), and a 350 kW, 0.4 GHz CW klystron for LHC in collaboration with Thales (France). Both designs use retrofit approach and are compatible with existing infrastructure. CERN has also undertaken the design and prototyping of a new klystron crucial to accelerate the electron beam of the future linear collider (FCC_{ee}). The paper will describe the changes of paradigm and innovations brought forward in recent years. The three prototypes mentioned will be described in some depth including the available experimental results.

† nuria.catalan.lasheras@cern.ch

THE DREAM

The high efficiency klystrons program at CERN

For most of the planned lepton colliders around the world, a large fraction of the required plug-power comes from RF (40 - 60 %) and, for most of these cases, the RF power is delivered by klystrons. It is then natural to search for the highest efficiency for these devices, defined as the ratio between extracted RF power and klystron beam power. In 2015, CERN launched a program together with university of Lancaster and SLAC to advance on the design of highly efficient klystrons required for high energy particle accelerators like the compact linear collider (CLIC), the international linear collider (ILC), or the future circular collider (FCC). This programme called the High Efficiency International Klystron Activity (HEIKA) [2] focused on benchmarking the different bunching techniques proposed in the past and developing new approaches to improve efficiency.

Klystrons dynamics

As illustrated in Figure 1, the RF power amplification in a klystron is achieved by bunching a DC beam of electrons with current I, emitted by a thermionic cathode and accelerated by a high voltage V. The beam travels through the input cavity which applies an RF field at the required frequency. The variable field seen by the electrons modulates their velocity, resulting in a beam bunched at the RF frequency. When this bunched beam traverses the output cavity laid at the proper location, most electrons are decelerated and generate a much higher signal and at the same frequency as the input one.

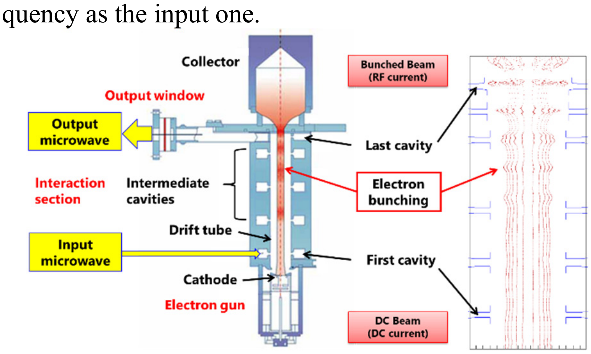

Figure 1: Simplified schema of a klystron tube. The beam density evolution along the channel can be seen on the right. Courtesy of CANON ETD.

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The decelerated electrons finish their journey in the collector. These spent electrons join all those who did not join the bunch at the output cavity and do not contribute to the extracted RF power. Maximum power is produced when the longitudinal density modulation is maximum at the output cavity. This is the principle of a two-cavities klystron while in practise, some passive cavities lay between input and output cavity to improve the bunching process. In general, the location, impedance and frequency of these cavities are optimised by numeric methods.

The perveance is an important beam parameter, connected with the klystron efficiency and defined as:

$$\mathrm{P} = \frac{I}{V^{\frac{3}{2}}}$$

This quantity, that can also be expressed as micro-perveance ($\mu P = P * 10^6$), is defined by the electron's emission from the cathode and the geometry of the gun in a space-charge limited regime. For a given beam power, high perveance means higher current and/or lower voltage, which means stronger space-charge forces. The interplay between the RF field generated in the cavities and space-charge forces inside the beam will determine the quality of the bunching and thus the efficiency of the klystron.

The bunching quality in a klystron is jeopardized by the variable nature of RF field in the cavities which delivers different velocity modulation to the electrons in the bunch core than to the ones on the periphery. Thus, not all the particles will arrive to the output cavity at the same time/phase. "Uncaptured" electrons in what is called the "anti-bunch" will arrive out of phase to the output cavity and will consume some RF power. To overcome such limitations, the Core Oscillation Method (COM) [3] was first introduced in 2014. It suggests increasing the distances between the cavities to allow the space charge to de-bunch slightly the bunch core, but to preserve almost laminar bunching of the peripheral electrons. The drawback of this approach is that the tube length shall be increased by a factor 2-3 compared to the classical bunching technique. Later, the Bunch-Align-Collect (BAC) method was developed to reduce the bunching length [4]. There, instead of de-bunching the core through the space forces, additional 'de-bunching' cavities (Align), capacitively tuned, are introduced together with second harmonic cavities (Collect) which accelerates the bunching of peripheral electrons. Altogether, the bunching length is reduced dramatically compared to COM, although it requires many cavities. The BAC concept was proven in two prototypes [5,6]. Finally, the Core Stabilisation Method (CSM) was proposed [7,8]. that uses second and third harmonic cavities in a bunching circuit. The harmonic cavities create sub-bunches in the core, which are then merged into a single bunch by the penultimate cavity of the klystron, while the peripherals electrons are strongly pushed towards the centre along the whole length of the tube. The CSM method was adopted for HE LHC 400 MHz klystron modification that will be introduced later, and for CEPC 800 MHz single beam and multi-beam HE klystrons [9].

Klystron simulations: KlyC suite

In 2017, CERN released a klystron optimization and simulation code called KlyC [10] which played an important role to facilitate the fast and accurate design of high efficiency klystrons. Space charge forces, relativistic and radial stratification effects were included in this 1.5 D code, which reached an accuracy of 2 % for the simulated efficiency when compared with results obtained with 3-D PIC commercial simulation packages like CST [11] or Magic [12]. KlyC simulates the beam along the klystron channel and performs optimization of parameters such as frequency and distance between cavities to maximize efficiency. The code also runs 100-1000 times faster than other commercial 3D codes which greatly facilitates design iterations. More advanced features such as coupling mode analysis, monotron oscillation predictions, DC gap acceleration, and complete small signal theory diagnosis have been added along the way to cope with instabilities, avoid reflected electrons or broaden the bandwidth. The code has since then been benchmarked by software developers, users and klystron manufacturers and continues to be fitted with new modules. A beam optics simulation tool (CGUN) is also included in the software package, which allow users to simulate 2D transverse optics problems.

KlyC is currently available in the public domain and is being used by different Labs (CERN, CEA, SLAC, KEK, PSI, and ESS) and industrial partners (Thales, CPI, Toshiba, VDBT, and BVERI) with this list continuously growing.

THE REALITY

State of the art

Figure 2 shows the efficiency versus the micro-perveance of the klystrons marketed for science (blue dots). As it can be seen from the plot, there is an empirical limit below which most of these klystrons lay, indicated as "industrial empirical limit".

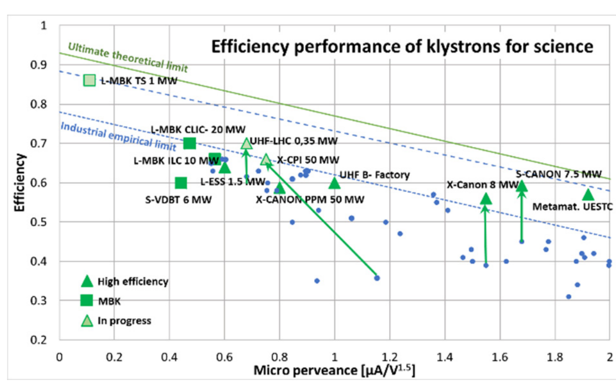

Figure 2: Efficiency versus micro-perveance for available commercial klystrons used for science. Green symbols denote high efficiency klystrons. Lighter green denotes tube under design or construction where the efficiency value is simulated. Green arrows indicate a redesign from an existing tube to retrofit on already operating facilities, generally without a change of perveance (vertical line).

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A number of multi-beam klystrons have been manufactured to improve efficiency at high power by keeping a very low perveance and reached efficiencies up to 70 %. According to [13], the efficiency limitation given solely by theory depends mostly on the output cavity transit time factor and the energy spread within an ideal bunch and it is shown as the "ultimate theoretical limit". We believe that applying a 5% reduction to that limit is a reasonable engineering result that can be attained.

X-band medium power

We will take as case study the example of the medium power, pulsed, high repetition rate tube E37113 manufactured by CANON ETD. It delivers a maximum power of 6 MW for a 5 µs pulse length and a repetition rate of 400 Hz. It has been in use in the X-band facility at CERN since 2017 where several periods of 24/7 operation are scheduled during the year for conditioning the CLIC accelerating structure prototypes. As part of their collaboration with CERN, CANON ETD built an upgraded version of the klystron on which they implemented a new vacuum window exhibiting approximately 30 % lower electrical field at the ceramic surface. The performance of the tube was identical to the previous version at the same conditions. However, a re-tuning of the gun allowed to increase the maximum cathode voltage from 155 to 175, thus increasing the peak power up to 8 MW. The efficiency of this tube was the same as the previous one, about 39 %.

In 2020, a new design of the klystron interaction structure based on the Core Oscillation Method and using a triplet of second harmonic coupled cavities was designed at CERN [14]. A three-cell output cavity follows a six-cavities bunching circuit, for a total length of 127 mm. The gun and collector are the same as for E37113 and so is the perveance. According to KlyC and CST simulations, the new tube was able to produce a power of 8 MW with the same beam current and voltage as the E37113 but at an efficiency of about 57 % as shown in Figure 3. Higher power was also within reach thanks to the improved window and gun.

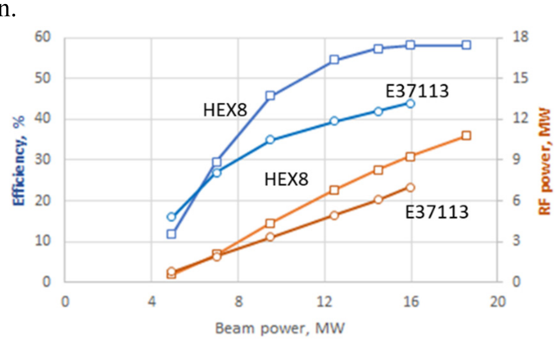

Figure 3: Comparison between the E37113 klystron commercialised by CANON ETD and the new design proposed by CERN.

In 2021, CANON ETD started the construction of the new tube according to the layout provided by CERN, and two tubes were ordered by the CLIC project. The first tube showed instabilities at cathode voltages above 70 kV. A prompt analysis by CERN found various coupled instabilities in the new bunching circuit. Long simulations, five microseconds into the pulse, done using CST fully reproduced the observed behaviour [15]. Modifications to the tube were introduced by the team at CERN to prevent the instability from growing. Lossy material was introduced in the first three drift tubes; the gap lengths of the first three bunching cavities were modified; and a doublet replaced the second harmonic triplet. A second tube was built following this new design (see Figure 4) while the first one was retrofitted with the revised RF circuit.

Figure 4: New E37117 build by CANON ETD in collaboration with CERN.

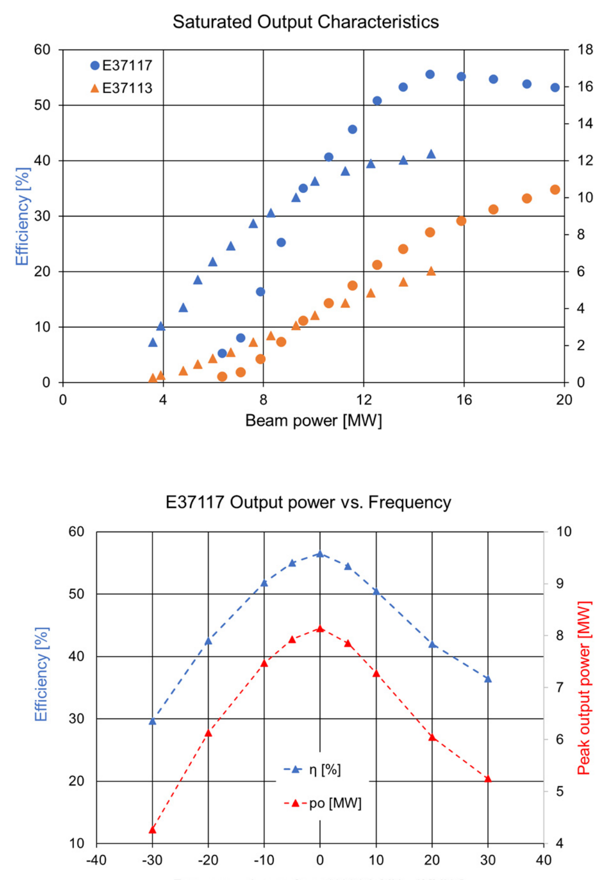

Figure 5: Performance measured at CANON ETD. Top: Output power and efficiency of E37117 tube (circles) comparison with the E37113 model (triangles). Bottom: Bandwidth measurement for the klystron E37117.

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The final performance of the klystrons with the above-mentioned modifications is shown in and Figure 5. The first tube tested in July 2022 showed a slightly lower efficiency than predicted. Further investigation revealed that the tuning of the output coupler did not match the simulations. A sweep in frequency showed that the maximum output power and efficiency was 30 MHz lower than designed. Nevertheless, the final efficiency at nominal frequency was 53 %.

The second tube was tested in November 2022, after refurbishment and a revision of the tuning procedure. The output peak power reached almost 10.5 MW and RF efficiency at optimised power level of 8 MW reached 56%, as predicted. It is also interesting to note that the efficiency stays above 50 % for output power between 6 to 10 MW. This new high efficiency klystron appears now in CANON ETD catalogue as E37117. All the interfaces with the modulator, solenoid, and waveguide systems were kept identical. Parameters for all three tubes can be found in Table 1.

Table 1: Parameters of the Three X-Band Klystrons Manufactured by CANON ETD for CERN

CANON ETD	E37113	E37123	E37117
Frequency		11994.2 MHz	
Repetition rate		400 Hz	
μPerveance		1.55 μP	
Beam voltage	157kV	176kV	153kV
Beam current	96A	115A	93A
Peak output power	6 MW	8 MW	8 MW
Efficiency	39%	39%	56%

CW UHF klystron for LHC

Sixteen klystrons working at a frequency of 400.8 MHz feed the superconducting cavities accelerating the proton beam in the Large Hadron Collider (LHC). The TH2169 klystrons manufactured by Thales have been in operation at CERN since 2008. As part of the CERN High efficiency program, it was envisaged to build a prototype to serve as a spare to the aging units. The prototype was partly financed by the EU as part of the IFAST program.

The parameters of the original and improved efficiency tube can be found in

Table 2.

Table 2: Parameters of the Original and Improved Efficiency Klystron for LHC

THALES	TH2169	TH2169 HE
Frequency	400.8 MHz	
Gun μPerveance	0.7 μP	
Beam voltage	58kV	58kV
Beam current	8.4A	9A
Output power	300 kW	365 kW
Efficiency	62%	70%

The tube is designed to reuse as many parts as possible to reduce the cost and to maintain compatibility with the LHC installation. The gun, output cavity and window are identical while the beam channel and the collector have been re-designed. The solenoid and the supporting frame are also reused with minor modifications.

Given the constrains of length and voltage which are imposed by the current LHC installation, the calculated efficiency of the new tube is a modest improvement from 62% to around 70 %. However, the main purpose of this design is to generate a higher power to accelerate the higher charge beams of the high Luminosity LHC (HL-LHC). We benefit thus from a higher efficiency to have an output power of 350 kW with the original high voltage generator and with almost the same tube length. The comparison between the old and new assembly can be seen in Figure 6.

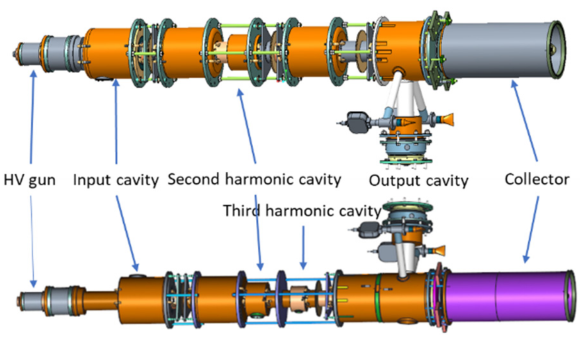

Figure 6: Comparison of the TH2169 klystron and his high efficiency counterpart.

The construction of the prototype started in 2022 with the validation of the design provided by CERN using in-house codes at THALES. The powering of the solenoid coils, the magnetic field longitudinal distribution and the positioning and length of some drifts had to be slightly re-adjusted to improve stability and to account for manufacturing constrains. The first experimental verification of the performance of the tube is what is called the vehicle test. For this test, the last two cavities of the tube shown in Figure 7 (right), which are most critical for the final performance, are manufactured and measured to check against the simulations. The frequency after manufacturing was within 3 MHz of the nominal and less than 0.1 MHz after tunning. The final assembly of the tube in Thales is currently ongoing, and the prototype will become available in the summer 2024.

Figure 7: Picture of the cavity subassemblies: Left: cavities 2,3 and 4. Right: penultimate and output cavity.

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The future: Two stage klystron for FCC

The last tube that we will present has a drastically different topology and uses an intermediate DC voltage post-accelerating gap in what is called a two-stage klystron.

The original idea to use a DC post acceleration (PA) of the pre-bunched beam in a single beam klystron was proposed in 1963 [16]. Experimental studies of this proposal were done few years later [17]. Recently, as an attempt to develop a technological solution for a HE, high power L- band klystrons, these ideas were revisited and further improved using the design of the CLIC MBK [18,19]. In its novel configuration with two stages (TS-MBK), the cathode and the two stages are connected in series. The high-voltage PA gap is located in the middle of the designated drift tube and separates the two stages, so that the second stage and the collector are connected to the ground potential. The first stage operates at a relatively low voltage, so that a high perveance beam is produced by the gun and the bunching circuit length can be rather short. In the second stage the beam is further accelerated in the high voltage PA gap, so that the beam perveance is decreased. The use of a penultimate cavity in the second stage is a novelty of this scheme, as it improves the bunching quality and helps to increase the RF power production efficiency. Such a topology was optimized for the FCC 0.4GHz, 1MW, CW Multi-Beam Klystron [20], shown in Figure 8 resulting in a very compact (3 m long) device.

Moreover, this design maintains a very high efficiency above 82 % in the full range of power levels requested by FCC by simply operating at different voltages [21], as shown in Figure 9.

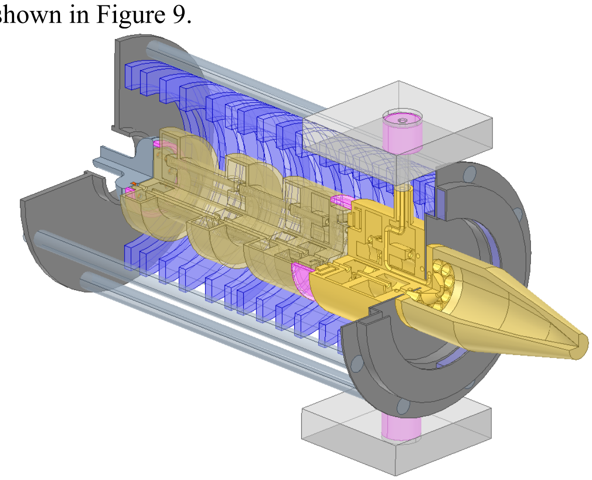

Figure 8: TS-MBK klystron.

The manufacturing of a prototype of this klystron is the current priority of the CERN program. If confirmed, it will demonstrate the highest efficiency of all existing klystrons.

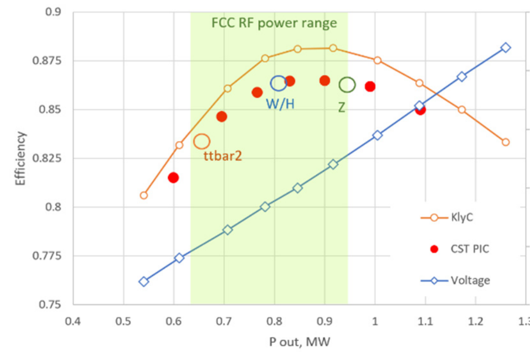

Figure 9: Efficiency and power delivered by the TS-MBK according to simulations. The green area represents the range of RF power required for the different physics stages of the FCC.

CONCLUSION

In the last years, we have witnessed an increasing interest on the design and prototyping of high efficiency klystrons. Fruitful collaborations between industry and research facilities have brought to reality tubes performing well beyond the established industrial limits. Besides particle physics, many other scientific and society projects will benefit from a reduced energy consumption. Besides the obvious advantage of a reduced electricity bill, the capital investment to own a RF system will also be reduced by the use of a smaller HV modulators, savings in a cooling system and increased lifetime of the tubes themselves.

In this paper, we have solely considered the conversion between the power of the electron beam and the extracted RF power from the klystron. However, other factors affect the wall-plug consumption of the global power source. The high voltage modulator conversion efficiency, the HV pulse forming network, or the operation of the klystron bellow saturation for feedback loop stability determine the final efficiency of the power source as a global system and deserve to be studied. Specifically, the power dissipated by the klystron electromagnet is relatively important in pulsed systems where the duty factor is very small. There are ongoing efforts to improve solenoid performance using superconducting [22] or permanent magnets technologies.

ACKNOWLEDGEMENTS

The prototype manufacturing of the TH 2169 HE klystron has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730.

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