

High-efficiency klystrons from a dream to a reality

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During the past decade, a comprehensive research and development (R&D) program on high-efficiency klystrons has been carried out in collaboration with industry. Initial prototypes have undergone testing, with experimental results showing significant promise. This paper is an extended and updated version of the work presented in Catalan-Lasheras *et al.* [JACoW **IPAC2024**, FRYD1 (2024)]. After a brief overview of the R&D program, it presents the latest experimental findings and discusses future developments, including novel vacuum tube topologies aimed at next-generation collider applications.

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I. INTRODUCTION

Since the first prototype built by the Varian brothers in 1937, klystron rf amplifiers have been used in particle accelerators and telecommunications, providing a reliable and cost-effective solution. For decades, this technology was considered 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 klystrons, with a record efficiency of 70% demonstrated in a few prototypes [1]. Already in 2010, CERN started exploring the possibility of enhancing klystron efficiency, with the objective of optimizing rf power generation and

reducing overall power consumption in large-scale accelerator facilities such as CLIC. In 2015, extensive studies of klystron technologies were established at CERN. This activity included development of new computer simulation tools [2] and in-depth studies of beam dynamics to understand the factors limiting the efficiency. As a result, a number of new methods for beam bunching were developed [3–6], which allowed increasing the klystron's rf power production efficiency by 10%–30%, compared to existing commercial devices. Under the CERN high-efficiency (HE) klystron program, two such klystrons have been produced 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 a retrofit approach and are compatible with existing infrastructure. CERN has also undertaken the design of a new klystron topology that could be used to power future colliders in the energy frontier, such as the Future Linear Collider (FCC), the International Linear Collider, or the Compact Linear Collider (CLIC), while collaborative efforts with the University of Lancaster are also advancing klystron development for potential application in a future muon collider. The paper will describe the paradigm shifts and innovations brought forward in recent years.

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The prototypes mentioned will be described in some depth, including the available experimental results.

II. THE DREAM

A. The high-efficiency klystron program at CERN

For all 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 with large peak and average power. 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.¹ In 2015, CERN launched a program together with the University of Lancaster and SLAC to advance the design of highly efficient klystrons required for high-energy particle accelerators. This program, called the High-Efficiency International Klystron Activity [7], focused on benchmarking the different bunching techniques proposed in the past and developing new approaches to improve efficiency.

B. Klystron dynamics

As illustrated in Fig. 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, where it interacts with an rf field at the required frequency. The variable field seen by the electrons modulates their velocity, resulting in a beam bunched at this rf frequency. When the bunched beam traverses the output cavity laid at the proper location, most electrons are decelerated and generate a much higher signal at the same frequency as the input one.

The decelerated electrons finish their journey in the collector, typically made of copper, where their energy is converted to heat and properly cooled. These spent electrons, together with those that never merged into the bunch at the output cavity, 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 working principle of a simple two-cavity klystron. In practice, some passive cavities lie between input and output cavities to improve the bunching process. The location, impedance, and frequency of these cavities were once approximated by analytical models and are nowadays optimized by numeric methods.

Let us introduce the perveance, an important beam parameter connected with the klystron efficiency and defined as

¹Unless otherwise stated, “efficiency” in this paper refers solely to the klystron dc-to-rf conversion efficiency at saturation. The power consumption of auxiliary power supplies and the efficiency of the power converter are excluded from this definition.

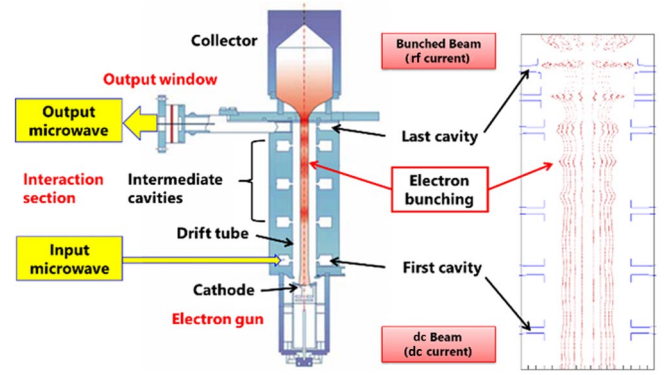


FIG. 1. Simplified schema of a klystron. The beam density evolution along the channel can be seen on the right. Courtesy of Canon ETD.

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

This quantity, which can also be expressed as microperveance ($\mu P = P \times 10^6$), is defined by the electron 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 translates into stronger space-charge forces. On the other hand, lower current and higher voltage both contribute to decreasing the same 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 efficiency of a klystron is inversely correlated with its microperveance. One way to improve efficiency is to use many low microperveance beams in what is called a multibeam klystron (MBK) to reach both high efficiency and high power.

The bunching process in a klystron is a very nonlinear process, driven by the interaction between the particles and the rf fields and by the space-charge forces inside the beam. As a result of this complex interaction, one of the factors limiting the klystron efficiency is the incomplete “bunch saturation”: due to the different velocity modulation of the electrons in the bunch core than to the ones on the periphery, not all the particles will arrive at the output cavity with the right phase in order to be decelerated. The electrons in what is called the “antibunch” 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 introduced in 2014. It suggests increasing the distances between the cavities to allow the space charge to debunch slightly the bunch core but to preserve almost laminar bunching of the peripheral electrons. The drawback of this approach is that the klystron length shall be increased by a factor of 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 debunching the core through the space forces, additional “debunching” cavities (Align), capacitively tuned, are introduced together with second-harmonic cavities (Collect) which accelerate 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 [8,9]. Finally, in the core stabilization method (CSM) [5,6,10], higher (second and third) harmonic cavities are used in the bunching circuit. The harmonic cavities create sub-bunches in the core, which are then merged into a single bunch by the penultimate cavity, while the peripheral electrons are strongly pushed toward the center along the whole length of the klystron. The CSM method was adopted for the LHC 400 MHz HE klystron modification that will be introduced later and for CEPC 800 MHz single-beam and multibeam HE klystrons [11].

C. Klystron simulations: KlyC suite

In 2017, CERN released a klystron optimization and simulation code called KlyC [2] which played an important role in enabling the fast and accurate design of high-efficiency klystrons. Space-charge forces, relativistic and radial stratification effects were included in this 1.5D code, which reached an accuracy of 2% for the simulated efficiency when compared with results obtained with 3D PIC commercial simulation packages like CST [12] or Magic [13,14]. 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, Canon, VDBT, and BVERI) with this list continuously growing.

III. THE REALITY

A. State of the art

Figure 2 shows the efficiency versus the microperveance of the klystrons marketed for science (blue dots) as given by the manufacturer. As it can be seen from the plot, there

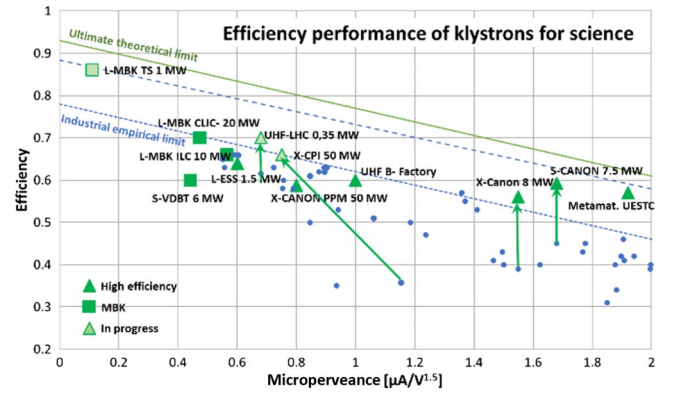


FIG. 2. Efficiency versus microperveance for available commercial klystrons used for science. Green, large symbols denote high-efficiency klystrons. Lighter green denotes klystrons under design or construction where the efficiency value is simulated. Green arrows indicate a redesign from an existing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

is an empirical limit below which most of these klystrons lay, indicated as “industrial empirical limit.” In the same plot, we have indicated with green symbols recent klystrons that have challenged this limit by designing for higher efficiencies using the approaches mentioned in Sec. II B. In some cases as indicated by the arrows, an existing klystron has been redesigned to fit the same operating slot but with an improved efficiency in what we called a “retrofit” of the system. Multibeam klystrons are indicated by square symbols.

According to [15], the efficiency limitation given solely by theoretical considerations on an ideal electron beam depends mostly on the output cavity transit time factor and the energy spread of the bunch. This theoretical limit is shown in the figure as the “ultimate theoretical limit.” We believe that applying a 5% reduction to that limit is a reasonable engineering result that can be attained.

B. X-band medium power developments

CERN high gradient facilities originally deployed to test CLIC prototypes have been employing X-band klystrons with peak power levels of 6 and 50 MW [16–19]. The maximum efficiency of these devices is below 45%, with more common values being even lower than 40%. On the lower power units, the Canon E37113 klystron is used whose main specifications are shown in Table I. This klystron has been in operation for several years in what is called the Xbox3 facility at CERN which combines two of these devices to provide pulsed power up to 45 MW. It has been the starting point for an research and development program, in collaboration with Canon, aiming at increasing the efficiency of the original klystron to above 50%. The aim of the program was to benchmark the increase in efficiency against the design values while achieving a

TABLE I. Canon X-band klystrons used in the X-boxes facilities at CERN: Main specifications.

Parameter	E37113	E37123	E37117
Frequency	11.994 GHz	11.994 GHz	11.994 GHz
Peak rf output power	6 MW	8 MW	up to 10 MW
rf pulse length	$\leq 5 \mu\text{s}$	$\leq 5 \mu\text{s}$	$\leq 5 \mu\text{s}$
Repetition rate	$\leq 400 \text{ Hz}$	$\leq 400 \text{ Hz}$	$\leq 400 \text{ Hz}$
Cathode voltage	155 kV	up to 175 kV	up to 175 kV
Cathode current	98 A	115 A	115 A
Average output power	12 kW	16 kW	16 kW
Gain	48 dB	...	...
Efficiency	39%	39%	56%

higher peak power to test prototypes to nominal CLIC conditions of about 60 MW.

At the beginning of the collaboration with CERN, Canon had produced a high-power version of the klystron, the E37123, featuring a new rf window and an upgraded gun, and able to deliver 8 MW output power, but still with an efficiency of 39%.

Based on this klystron, CERN designed a new interaction structure, including a second-harmonic triplet and a three-cell output cavity [20], allowing an increase in the efficiency to 56% by maintaining the E37123 gun and output window design and reusing the original solenoid.

Canon manufactured a first prototype, the E37117 S/N 22M001; however, during initial tests in diode mode, the klystron presented a monotron oscillation at frequencies around 22.5 GHz, arising for cathode voltages between 70 and 125 kV. It also showed instabilities due to coupled TE_{11} modes above 107 kV [21]. Subsequent investigation and simulations by the CERN team [22,23] pointed out that the issue could be solved by: (i) replacing the second-harmonic triplet with a doublet; (ii) varying the gap lengths of the first three bunching cavities, and (iii) adding stainless steel in the drift tubes to increase the onset current of the oscillations above the operating beam current.

All three modifications were implemented in the second prototype built by Canon, the E37117_CAV_CHG S/N 22G002. This klystron showed the highest efficiency about 30 MHz below the design frequency during the initial test at Canon, as shown in Fig. 3, but still with a remarkable efficiency of 53% at the design frequency.

The possible reasons for this difference were analyzed by CERN and Canon, and it was found that the frequency of the first and second cells of the three-cell output coupler was lower than the design value [24]. However, the klystron was delivered to CERN with no further modification.

The design and manufacturing issues were addressed while rebuilding the first klystron at Canon, the E37117 S/N 22M001. This klystron was refurbished, including the modified interaction structure to suppress the oscillations, and then successfully tested with no sign of instability up

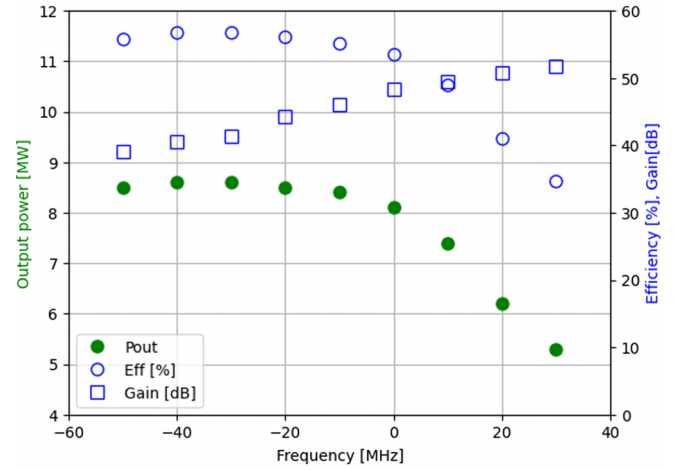


FIG. 3. E37117 S/N 22G002 factory test results.

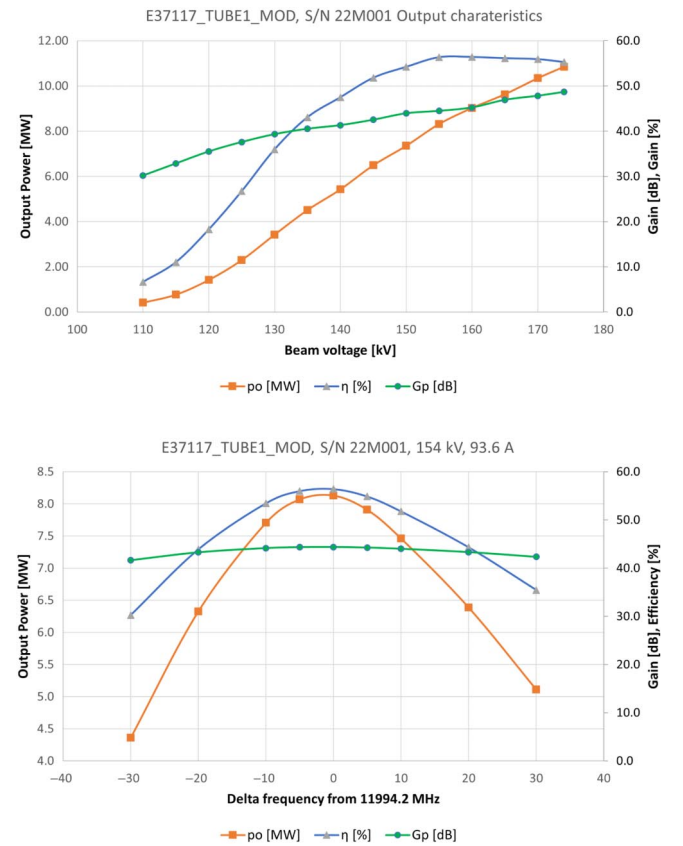


FIG. 4. E37117_TUBE1_MOD, S/N 22M001 factory test results.

to 170 kV, reaching 56% efficiency, as predicted in the simulations (Fig. 4).

The klystron was then delivered to CERN, where the performances were confirmed, as shown in Fig. 5 [25].

This klystron is capable of delivering 8 MW of peak power with the same dc power consumption as the original E37113. Moreover, it can achieve up to 10 MW output power when the voltage is increased to 175 kV.

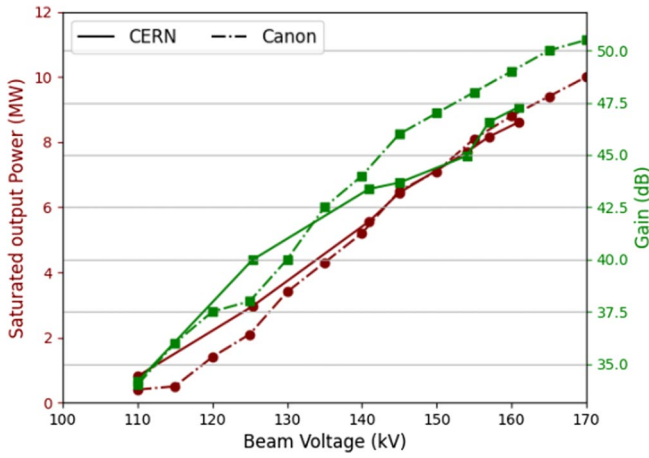


FIG. 5. E37117_TUBE1_MOD, S/N 22M001 test results at CERN and at Canon.

This achievement not only highlights the success of the collaboration between CERN and industry but also serves as a strong validation of the advanced bunching techniques used to attain high efficiency, as well as the simulation tools and expertise developed over years of high-efficiency research.

C. CW UHF klystrons for HL-LHC: motivation and constraints

The High Luminosity LHC (HL-LHC) will operate with high-intensity proton beams containing up to 2×10^{11} protons per bunch, effectively doubling the standard bunch intensity used in the current LHC.

This increase in beam intensity results in substantial beam loading and necessitates higher rf voltages to efficiently capture and maintain beam stability [26,27]. Consequently, the existing rf system is expected to operate at the edge of its 300 kW power capacity. To accommodate these greater demands, the current klystrons will be upgraded to high-efficiency units capable of supplying 350 kW of rf power, while still operating within the same dc power input constraints from the current modulators.

A collaboration was established in 2019 with Thales to design and produce a high-efficiency version of the TH2167 klystron, in the framework of the Innovation Fostering in Accelerator Science and Technology (I.F.AST [28]) project—work package 11.2. The project aimed at producing a technology demonstrator for the new bunching techniques to increase klystron efficiency, while at the same time meeting the requirements of the High Luminosity Large Hadron Collider (HL-LHC). The project targeted achieving a saturated output power of 350 kW at the existing operating point (58 kV, 9 A) to ensure compatibility with current power supplies [29]. This requires improving the klystron efficiency from 60%–62% to around 67%–68%, with the new design enabling plug-in replacement of the existing klystrons. The main

TABLE II. TH2167 and TH2167HE main specifications.

	TH2167	TH2167HE
Frequency	400.8 MHz	400.8 MHz
Cathode voltage	58 kV	58 kV
Cathode current	8.5 A	9 A
Modulating anode voltage	≤ 35 kV	≤ 35 kV
Output power (saturation)	300 kW	350 kW
Gain	≥ 37 dB	≥ 35 dB
Efficiency	$\geq 62\%$	$\geq 68\%$
Bandwidth (-1 dB)	$\geq \pm 1$ MHz	$\geq \pm 0.7$ MHz
Group delay	≤ 120 ns	≥ 120 ns
Harmonics (2nd, 3rd)	≤ -30 dB	≥ -30 dB

specifications of the TH2167HE and TH2167 klystrons are shown in Table II [30,31].

1. Design: High-efficiency bunching circuit and main simulation results

The technical approach employs an interaction structure designed by CERN using KlyC. Applying the CSM as described in Sec. II B, a compact six-cavity design has been proposed, with predicted efficiency of 70%–72%.

Cost efficiency is achieved through a redesign of the interaction structure, leveraging the reuse of critical components, including the solenoid, air gun tank, coax-to-waveguide transition, and support frame, repurposed from decommissioned LHC klystrons.

The main results from KlyC simulations of the new interaction structure are shown in Fig. 6: after several iterations, the cavity frequencies were optimized to accommodate the LHC LLRF requirements in terms of bandwidth and group delay, and the position and geometry of the penultimate cavity were modified to meet cooling system constraints.

A comparison between the original TH2167 design and the new high-efficiency version is shown in Fig. 7 [32]: the final structure is nearly 200 mm shorter than the TH2167, and KlyC simulations predict an efficiency of 70.8% with a gain of 37.2 dB, without reflected electrons. This represents an increase in efficiency of about 8% over the TH2167.

Similar results were obtained by Thales using their in-house code klys2D, which predicts efficiencies of 67% for the high-efficiency design and 60% for the original

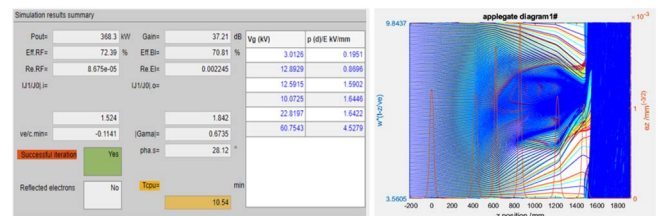


FIG. 6. Main results of the TH2167HE interaction structure simulation in KlyC.

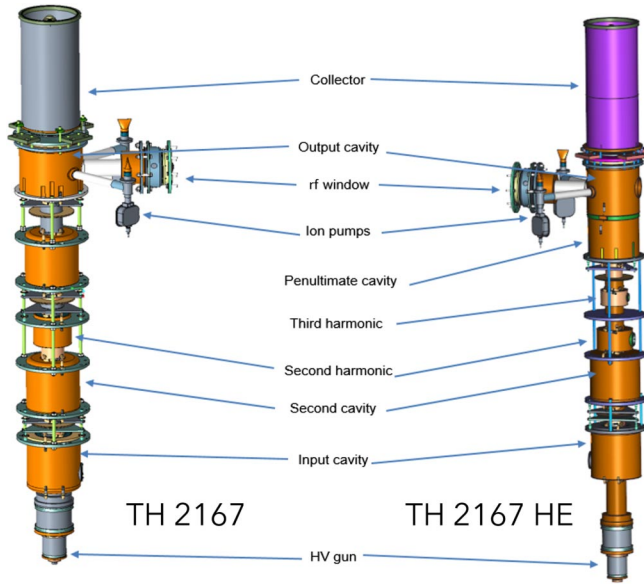


FIG. 7. Comparison of TH2167 and TH2167HE designs.

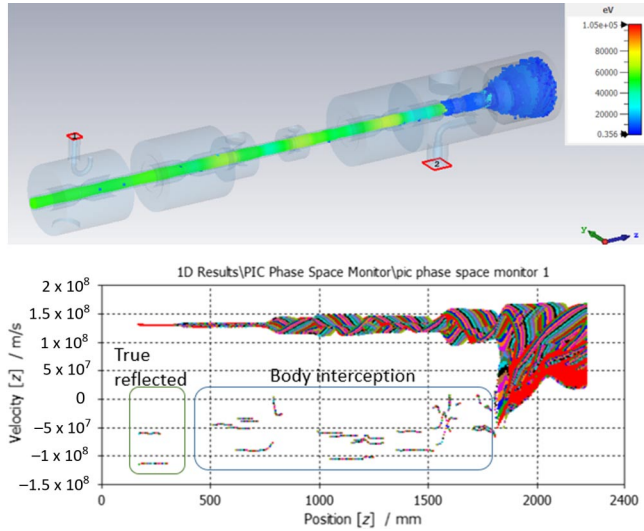


FIG. 8. Simulation of the interaction structure of the TH2167HE in CST.

TH2167. However, reflected electrons are predicted by klys2D for the high-efficiency interaction structure.

A more precise estimate of the new design's performance can be achieved through simulation using the CST Particle-in-Cell (3D) solver [12,33]. The CST simulation predicts an efficiency of 70.85%. While a small number of reflected electrons are observed (as shown in Fig. 8), this is not expected to impact operation, as most are intercepted by the klystron body, resulting in a negligible body power of only 20 W. Nevertheless, it was decided during the design phase to provide a separate power supply for the last two solenoid coils. This allows for independent adjustment of the current, offering additional control over the reflected electrons without significantly affecting the overall efficiency.

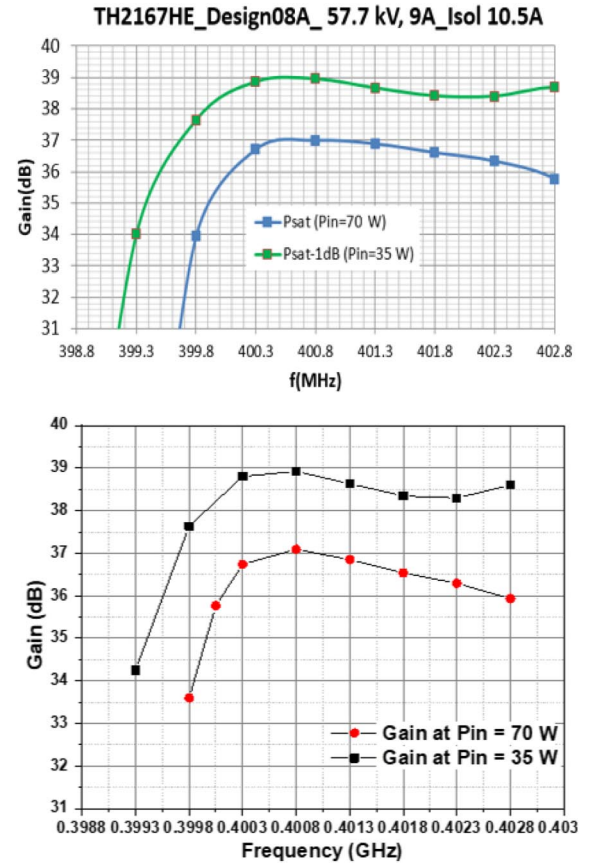


FIG. 9. Bandwidth at saturation and 1 dB below saturation simulated in klys2D (top) and CST Particle Studio (bottom).

Figure 9 shows the bandwidth at saturation and at saturation -1 dB simulated by Thales (klys2D) and CERN (CST PIC). The two simulation codes showed strong agreement, and they both indicated a sharp drop in klystron gain at the lower end of the frequency band. This behavior is attributed to the influence of the harmonic cavities. Nevertheless, the final klystron bandwidth remains within the specifications required for HL-LHC operation.

2. Manufacturing and test at Thales

Manufacturing at Thales began after the successful validation of brazing procedures for the subassembly of the final two cavities and the coaxial output (shown in Fig. 10), which was demonstrated through the construction of a test vehicle, a dedicated prototype assembly built to qualify the brazing process and verify the mechanical and rf performance prior to series production.

To address the new mechanical constraints related to cavity positioning and to simplify the overall design, a radial tuning system was selected for the harmonic cavities (cavities 3 and 4) and the output cavity (cavity 6), replacing the mobile drift adjustment approach typically employed by Thales in standard klystron configurations.

The collector was also modified, increasing both its length and diameter, to provide a greater safety margin



FIG. 10. Penultimate and last cavity before assembly.

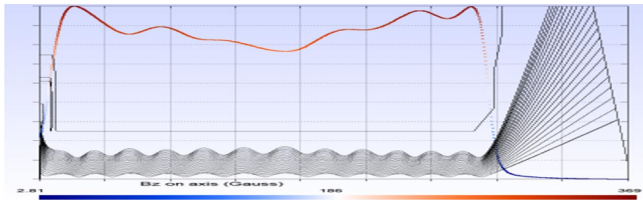


FIG. 11. Simulated beam transport and spread in the new interaction structure of the TH2167HE.

compared to the TH2167. This redesign aimed to lower power density, addressing issues encountered in early TH2167 units, and to accommodate the potential need for higher beam power if the efficiency margin proved to be insufficient to achieve 350 kW output at 58 kV and 9 A.

To accommodate the new interaction structure, the solenoid design was slightly revised by repositioning three of the coils to align with the updated cavity locations. These adjustments have shown no adverse effect on overall beam focusing, as it can be seen in Fig. 11. As mentioned, the final two coils were decoupled from the main solenoid and configured to operate with an independent power supply, providing greater flexibility in controlling reflected electrons.

The modified solenoid, along with the klystron frame, gun tank, and output coaxial-to-waveguide transition, were reused from TH2167 S/N 1, which was removed from the LHC in 2022.

3. Main issues during initial testing

During initial rf tests in pulsed mode at the Thales factory, a significant increase in the temperature of the

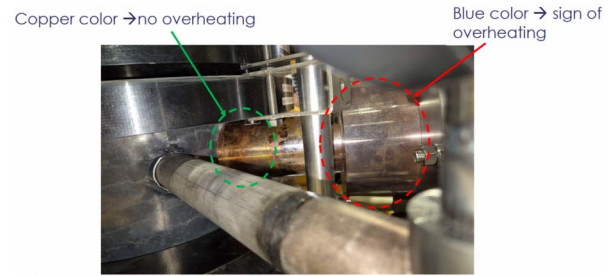


FIG. 12. Discoloration of copper indicating overheating on the outer coaxial.

output coaxial at output power levels below 100 kW was measured and confirmed by discoloration of the copper on the top side of the coaxial (Fig. 12). Both the power and phase transfer curves showed disturbances: the phase response was nonmonotonic, and the power curve exhibited a small step. Additionally, the rf pulse was also affected and distorted at power levels below 200 kW (Fig. 13).

The overheating of the coaxial and the signature in the rf tests pointed to multipacting in the region of the output coaxial just before the ceramic window, confirmed by CST simulations [34], as shown in Fig. 14. The simulation also showed that the secondary emission could be reduced by applying a static magnetic field either in longitudinal direction (parallel to the coaxial axis) or transverse

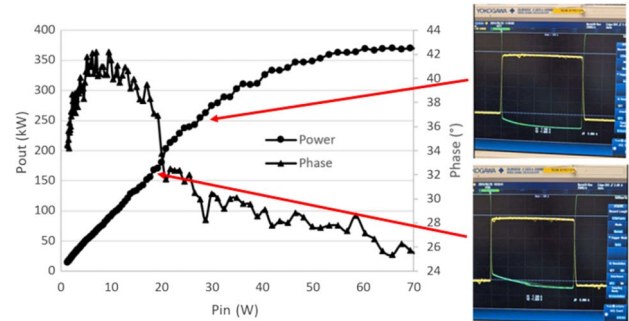


FIG. 13. Transfer curve (left) and rf output pulse (right) showing disturbances in the 0–200 kW region of output power.

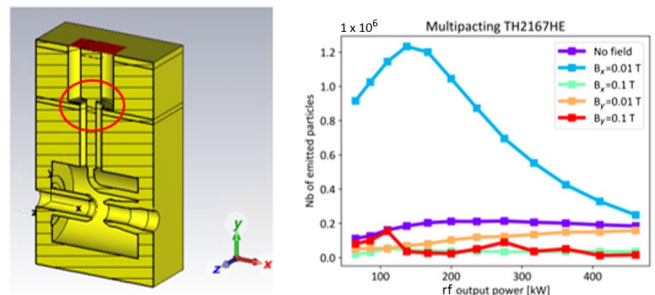


FIG. 14. Reduction of emitted particles with application of a static magnetic field (CST simulation)—courtesy of F. Peuger.

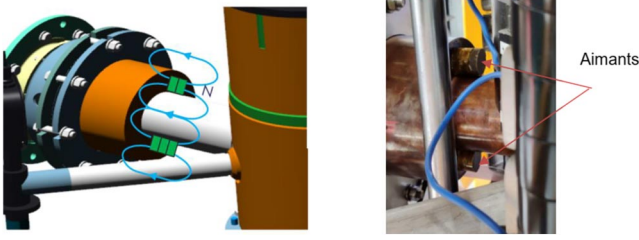


FIG. 15. Installation of magnets on the output coaxial to correct the multipacting.

(perpendicular to the coaxial direction). The preferred choice in terms of implementation was to apply a field in the longitudinal direction by installing permanent magnets on the external surface of the coaxial, as shown in Fig. 15.

After installing the magnets, the klystron exhibited a smooth and consistent output transfer curve for both power and phase. Additionally, the overheating issue in the output coaxial line was resolved, confirming the effectiveness of the corrective action.

A second issue identified during factory testing was a significant reduction in prototype performance, particularly in efficiency and gain. The measured gain was approximately 3 dB below expectations, and the maximum output power did not exceed 300 kW. As white-noise measurements had already verified correct tuning of cavities 1, 2, and 5, the initial hypothesis was that the second-harmonic cavity was detuned. Bandwidth measurements done by Thales were also performed and compared with KlyC simulations to confirm the possible detuning of the second-harmonic cavity toward higher frequency than the design one, as shown in Figs. 16 and 17.

Thales used the external tuning mechanism to correct the cavity frequency and observed significant improvement in the klystron performance. However, the tuning range was not sufficient to reach the correct frequency; therefore, it was decided then to release slightly the bolts

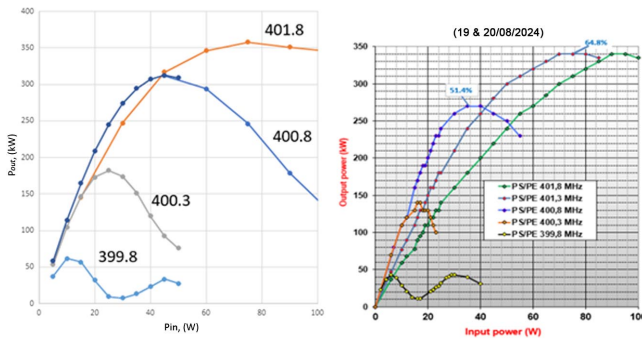


FIG. 16. KlyC simulations (left) and Thales measurements (right): in the KlyC model, the second-harmonic cavity was detuned at 799.2 MHz (with design tuning being at 797.3).

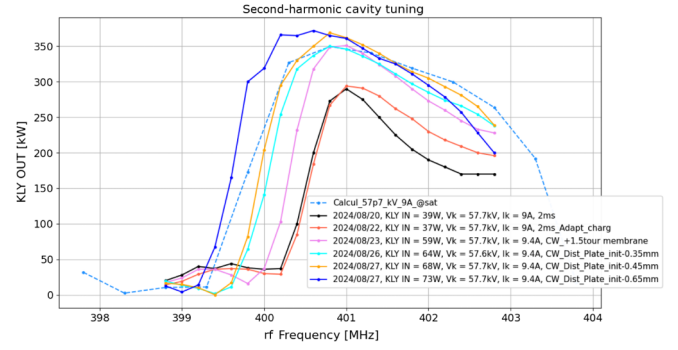


FIG. 17. BW measurements for different settings of the second-harmonic cavity tuning system (membrane) and deformation of the cavity walls (plate distance).

of the supporting frame to deform (compress) the cavity walls by using the weight of the klystron itself. Additionally, the focusing magnetic field was carefully adjusted to achieve the desired performances and at the same time avoiding reflected electrons (detected by observing the spectrum of the output signal). Following measurements showed results in agreement with the simulation predictions, with output power exceeding 360 kW at 58 kV and 9 A.

Temperature monitoring of the new tuning system implemented on the harmonic cavities revealed significant thermal constraints during rf testing. Thermocouples installed on the tuning membranes recorded temperatures exceeding 100°C, with peaks reaching up to 300°C when operating at lower frequencies, even at reduced output power. This overheating was attributed to the tuning system design, which relies on joints with poor thermal conductivity to the main cavity body. As an interim mitigation, additional air cooling was implemented on the prototype's harmonic cavities, while a revised tuning-system design with improved thermal performance has been defined for series production.

The full factory acceptance test completed at Thales confirmed that the klystron achieved the expected efficiency, gain, and stability, showing excellent agreement with KlyC predictions corrected for the measured cavity frequencies (Fig. 19). The main test results are shown in Table III.

TABLE III. Main results of factory acceptance tests.

Cathode voltage	57.7 kV
Modulating anode voltage	32 kV
Cathode current	9 A
Output power at saturation	366 kW
Input power at saturation	62
Gain	37.6
Efficiency	70.4%

4. Installation and testing in the CERN LHC klystron test stand

The TH2167 high-efficiency prototype was installed on the CERN test stand for full validation prior to series production.

Figure 18 shows the klystron in its test configuration, including air cooling applied to the harmonic cavities and additional instrumentation to monitor the temperatures of the harmonic cavities and the output coaxial line during operation.

Under these conditions, and following standard dc and rf conditioning, the klystron achieved a saturated output power of 357 kW at a cathode voltage of 57.3 kV and a beam current of 9.05 A. rf power measurements were carried out after careful calibration of the input and output lines, with an estimated measurement uncertainty of approximately 4%. At saturation, the measured efficiency was 68.9%, with a gain of 35.5 dB. The transfer curves measured at Thales and CERN, and the simulated one are shown in Fig. 19.

Bandwidth measurements were used to assess the tuning of the second-harmonic cavity and to exclude possible detuning during transport. These measurements were complicated by significant heating of the harmonic cavities at frequencies below nominal, with the third harmonic cavity approaching 150°C below 400.4 MHz and a corresponding slow increase in output power of up to 20 kW, likely driven by temperature-induced detuning. To limit thermal effects, the bandwidth was therefore measured in



FIG. 18. TH2167HE prototype installed in the CERN test stand.

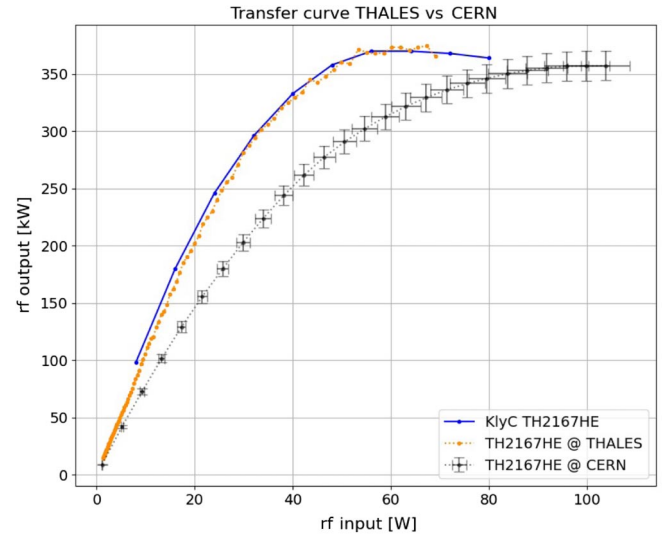


FIG. 19. Transfer curve measured at Thales and at CERN and simulated with KlyC (CERN code) showing 69%–70% efficiency. The measurement performed at CERN exhibits a slightly different gain, most likely due to calibration discrepancies in the rf drive chain.

pulsed mode, using 2 ms pulses at a 10 Hz repetition rate. Although reduced gain was observed at lower frequencies in pulsed mode, a measurable change in output power was still present down to 398.8 MHz. A comparison between the CERN measurements and those performed at Thales after final cavity and solenoid tuning is shown in Fig. 20, with the Thales data scaled by 2% to account for calibration differences at the central frequency. While it is not possible to determine if any transport-induced detuning of the second-harmonic cavity occurred, the bandwidth measured at CERN appears narrower on the low-frequency

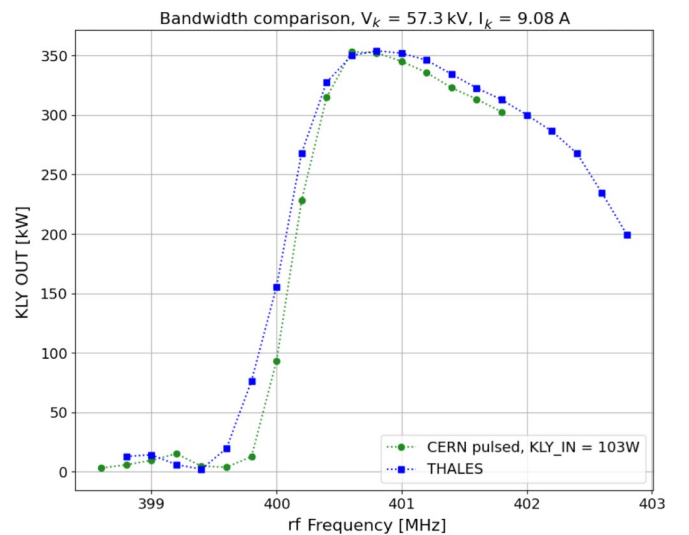


FIG. 20. Bandwidth measurements performed at Thales (cw) and at CERN (pulsed mode).

side, due to the fact that the measurements at Thales have been performed in cw.

Saturation curves were measured at CERN for several cathode voltage levels under two operating conditions. The first configuration reproduced the present LHC operating mode, in which the cathode voltage is varied without modifying the modulating anode control percentage. The second configuration maintained constant perveance by adjusting the modulating anode control at each voltage, in order to evaluate the potential efficiency benefit of this approach. In both cases, the focusing currents were kept unchanged (Fig. 21).

5. Comparison with KlyC simulation code

Following measurements done at Thales and at CERN, a new set of simulations was performed in KlyC, to benchmark the results and obtain a final “digital twin” of the delivered klystron. The benchmark was done in several steps: (i) The simulation was performed based on the cavity frequency measured with the white noise method, both at Thales and at CERN, which allowed measurement of the frequency of the input, second, and fifth cavities: a waveguide to coax transition was installed at the output of the klystron, and the output signal was observed with a spectrum analyzer at nominal beam voltage and current (no rf input). (ii) The frequency of the harmonic cavities and the beam radius were adjusted in the simulation in order to obtain a good agreement between the measured bandwidth and the simulated one, especially at the lower frequencies. (iii) The output line, from the klystron output flange to the ferrite load was measured, and the corresponding mismatch was introduced in the KlyC simulation. The result of such benchmark is shown in Fig. 22,

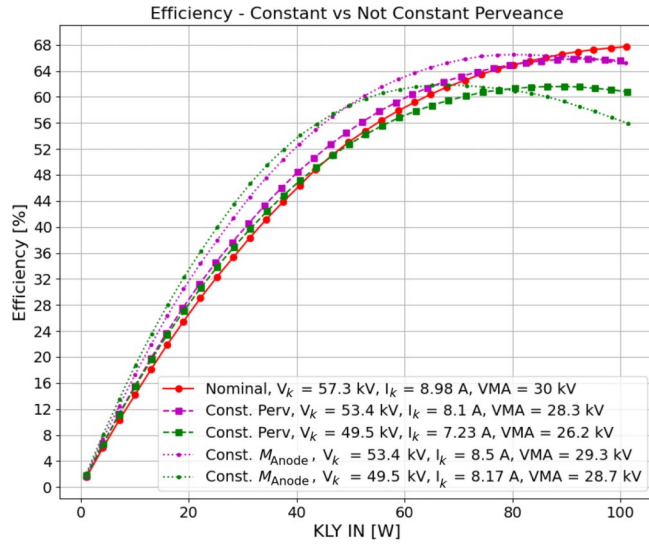


FIG. 21. Efficiency curves for different cathode voltage levels with constant perveance (dashed) and constant modulating anode control (dotted).

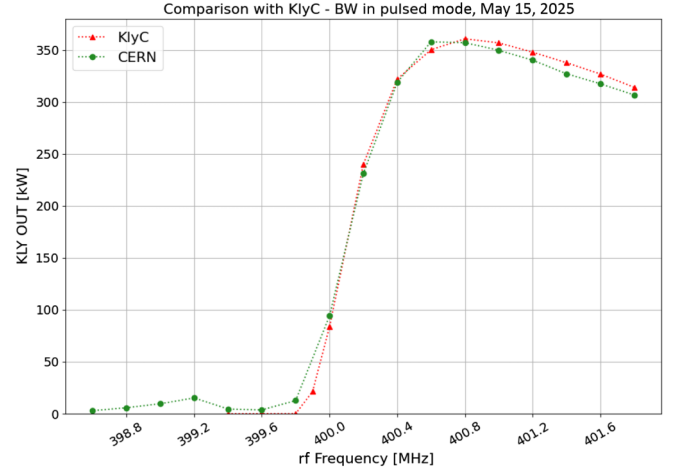


FIG. 22. Comparison between the updated KlyC simulation and the CERN measured bandwidth.

showing a very good agreement between the simulation and the measurement.

Finally, Table IV presents the differences in cavity tuning between the original TH2167HE design and the manufactured klystron, with the final values determined through measurements and validated by simulation benchmarks.

D. The future

Recently, as an attempt to develop a technological solution for a high-efficiency, high-power L-band klystrons for CLIC MBK [35,36], we revisited the idea to use a dc post acceleration (PA) in a single-beam klystron as proposed in 1963 [37] and demonstrated a few years later [38]. 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

TABLE IV. Main results of factory acceptance tests.

Cavity N	Delta frequency (MHz)
Cavity 1	−0.4
Cavity 2	−0.7
Cavity 3 (second harmonic)	−0.04
Cavity 4 (third harmonic)	0.5
Cavity 5	3
Cavity 6	0

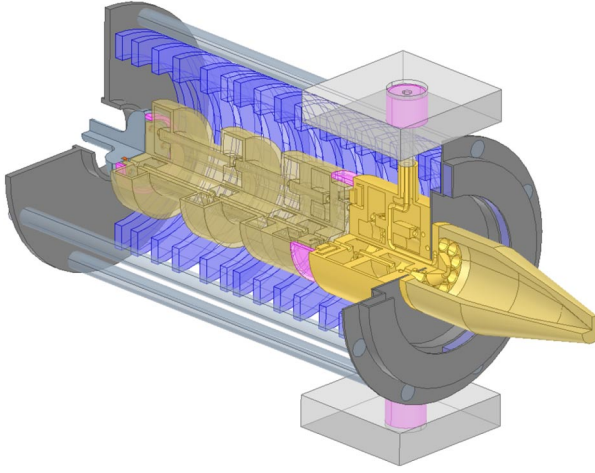


FIG. 23. TS-MB klystron.

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 also optimized for the FCC 0.4 GHz, 1 MW, cw Multibeam Klystron [39], shown in Fig. 23 resulting in a very compact (3 m long) device. 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 [40], as shown in Fig. 24.

A klystron typically achieves its highest efficiency only at saturation. In practical operation, however, the need to operate in the linear region of the klystron transfer function for LLRF regulation significantly reduces the achievable operational efficiency. In contrast, in gridded tubes such as IOTs, a reduction in drive power results in a corresponding decrease in the current drawn from the power supply, allowing the tube to maintain high operational efficiency even at reduced input power levels.

The tristrion [41,42]—whose name reflects its hybrid nature between a triode and a klystron—is a gridded tube

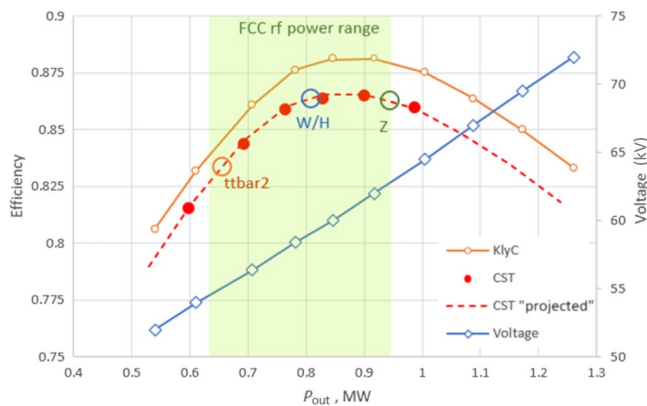


FIG. 24. Efficiency and power delivered by the TS-MBK according to simulations. The green area represents the range of rf power required for the different physics stages of the FCC.

similar to an inductive output tube (IOT), but capable of increasing efficiency from about 70% (typical for conventional IOTs working in B class) to above 90%. Compared with an IOT, the tristrion incorporates an additional idler cavity placed before the output cavity. This significantly improves electron bunching quality and therefore increases the overall efficiency while keeping the class B operation and therefore allowing to keep high average beam current.

The output rf circuit of the Tristrion can be nearly identical to the rf circuit of the second stage of a two-stage (TS) klystron. As the electron bunches are already fully saturated and better compressed, the rf power conversion efficiency can be further increased, reaching values above 90% for class-B devices operating at sufficiently low perveance. A multibeam (MB) tristrion is being studied and optimized at CERN as a candidate rf power source for FCC_{ee} [43]. The final design, consisting of ten beams and operating at 400 MHz with an output power of 460 kW at 46 kV (perveance of $0.11 \mu\text{A}/\text{V}^{3/2}$), demonstrated excellent performance in the rf power range from 400 to 500 kW, with efficiencies exceeding 90% [44], as shown in Fig. 25.

An artistic rendering of the FCC_{ee} multibeam tristrion is shown in Fig. 26.

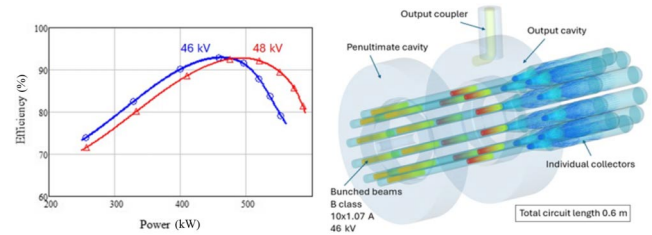


FIG. 25. Power/efficiency performance of the tristrion simulated in CST at different operating voltages for FCC_{ee} (left) and snapshot of particle dynamics (right).

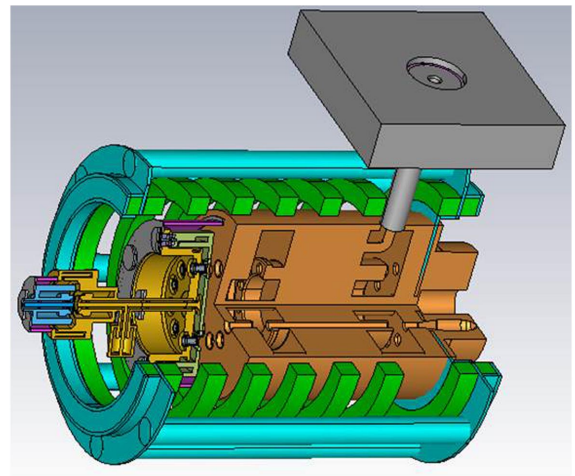


FIG. 26. Artistic view of the FCC_{ee} multibeam tristrion.

IV. SUMMARY AND CONCLUSIONS

The CERN High-Efficiency Klystron Program, now spanning over a decade, has led to significant advancements in the understanding and implementation of high-efficiency klystron design. Through sustained research and development efforts, the program has identified and validated key mechanisms that enable enhanced performance in klystron technology. These insights have been successfully translated into working prototypes, developed in close collaboration between CERN and industrial partners. This partnership proved instrumental in overcoming numerous technical challenges encountered during the prototyping phase, demonstrating the value of combining scientific research with industrial expertise. The outcomes of this program not only represent a substantial step forward in rf power source technology but also lay a strong foundation for future developments in high-efficiency accelerator systems.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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