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Design considerations for a $TE_{28,12}$-mode 2-MW, 140-GHz gyrotron for the ECRH system at W7-X

Emmanouil Deliprimis [a,*], Zisis C. Ioannidis [a], Konstantinos A. Avramidis [b], Tobias Ruess [c], Stefan Illy [c], John Jelonnek [c], Manfred Thumm [c], Ioannis G. Tigelis [b]

[a] National and Kapodistrian University of Athens, Department of Aerospace Science and Technology, Psachna, Greece
[b] National and Kapodistrian University of Athens, Department of Physics, Athens, Greece
[c] Karlsruhe Institute of Technology, Institute for Pulsed Power and Microwave Technology, Germany

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ABSTRACT

Following the recent upgrade of the Electron Cyclotron Resonance Heating (ECRH) system at the stellarator Wendelstein 7-X (W7-X) with a 1.5-MW, 140-GHz gyrotron (TH1507U), efforts are now focused on further advancing gyrotron technology by developing a 2-MW, 140-GHz Continuous Wave (CW) prototype. This paper proposes two RF and electron beam optics designs of a conventional-cavity 2-MW, 140-GHz gyrotron, operating with the $TE_{28,12}$ mode. Each design corresponds to different operating conditions, namely Low-Voltage High-Current (LVHC) and High-Voltage Low-Current (HVLC). The primary objective of the work is to leverage the existing infrastructure at W7-X while minimizing design modifications to the existing 1.5-MW gyrotron, therefore ensuring cost efficiency and increasing the possibility for a rapid implementation of the proposed designs. Given the significant (and challenging) space-charge depression associated with the $TE_{28,12}$ mode, several gyrotron startup scenarios are investigated thoroughly using the existing TH1507U diode Magnetron Injection Gun (MIG) as well as a new triode-type MIG design, which is based on the diode design. The findings of this study offer key insights into the design and operational challenges of future 2 MW-class gyrotrons operating at 140 GHz and beyond.

1. Introduction

The current Electron Cyclotron Resonance Heating (ECRH) system in the Wendelstein 7-X (W7-X) stellarator aims at providing 10 MW of plasma heating power, generated by ten gyrotrons operating at 1 MW each, at 140 GHz [1]. To meet the increasing power demands required for higher-performance stellarator operation, a phased upgrade of the installed ECRH power is planned over the next decade, increasing from 10 MW to 18 MW [2]. This has led to the design and development of a 1.5 MW gyrotron [3–5] and plans for 2 MW gyrotrons [2].

The industrial TH1507U 1.5-MW gyrotron, operating in the $TE_{28,10}$ mode, was delivered to W7-X in April 2024. Short-pulse tests (1 ms) confirmed the nominal output power of 1.5 MW. In long-pulse operation, the gyrotron achieved an output power of 1.3 MW with a total efficiency of 45.9 % at pulse lengths of up to three minutes. Continuous Wave (CW) operation was demonstrated with 580-second pulses, delivering 1.2 MW —setting a worldwide record in its category [5–7].

To progress towards 2 MW, it is crucial to change to a higher-order mode (compared to $TE_{28,10}$), to maintain the Ohmic loading of the cavity wall at technologically acceptable levels. Of course, by increasing the mode order, mode competition becomes stronger making stable and efficient operation more challenging. The challenge is even larger if it is desired to minimize the risk associated with the 2-MW gyrotron development and to maximize the use of the existing infrastructure at W7-X. These two aspects are indeed critical, given the tight schedule for the 2-MW gyrotron development, as part of the plan for the ECRH upgrade at W7-X [2]. Therefore, the scope of this paper is to investigate the possibilities for the development of a 2-MW, 140-GHz gyrotron with minimum risk and maximum utilization of the already available infrastructure at W7-X.

Essentially, 2-MW gyrotron short-pulse (up to 50 ms) operation has only been demonstrated by coaxial gyrotrons, which offer enhanced mode selectivity [8,9]. Therefore, a promising strategy for developing a 2-MW, 140-GHz gyrotron for W7-X would be to consider a coaxial gyrotron. However, the coaxial design introduces increased technological complexity, raising development risks. Consequently, this study

* Corresponding author.
E-mail address: mdeliprimis@aerospace.uoa.gr (E. Deliprimis).

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explores the possibility of achieving 2-MW operation with the conventional gyrotron concept, employing a hollow cylindrical cavity. To further mitigate risks, our study is based on the proven design of the TH1507U gyrotron as the basis for the 2-MW gyrotron development.

This paper is organized as follows: Section 2 outlines the main considerations and details the selection of the operating mode and operating parameters. Section 3 presents the results of the multi-mode simulations of the proposed designs in long-pulse operation. Section 4 thoroughly investigates the gyrotron start-up phase considering the existing TH1507U cathode block. Finally, Section 5 examines the gyrotron start-up phase with a triode-gun configuration, where the TH1507U diode electron gun is modified to a triode gun capable of delivering the required beam parameters to achieve similar gyrotron operation. Section 6 summarizes the study.

2. Selection of operating mode and operating parameters

To fully utilize the existing infrastructure at W7-X while minimizing modifications to the existing 1.5-MW TH1507U tube design, three key points must be considered: (i) ensure that the proposed operational parameters do not push the W7-X High-Voltage Power Supplies (HVPS) to their limits, (ii) maintain the same magnetic field profile, and (iii) keep the same cathode block as in the TH1507U gyrotron.

The nominal operating point for the existing 1.5-MW, 140-GHz $TE_{28,10}$-mode gyrotron for W7-X requires an accelerating voltage $V_{acc} \approx$ 82 kV (corresponding to 80 keV kinetic energy for the electrons, assuming 70 % neutralization [3] of the beam space charge) and an electron beam current $I_b = 55$ A. The cavity of this gyrotron is designed to achieve an electronic efficiency (or interaction efficiency), defined as the average electron energy loss from the beam-wave interaction [10], close to the theoretical maximum [3]. Therefore, to increase the output power to 2 MW, the electron-beam power must be increased, which can be achieved by raising the accelerating voltage and/or the beam current. The power supply capabilities at W7-X are: cathode voltage $V_c < 65$ kV, beam current $I_b < 100$ A, and body voltage $V_b < 32$ kV. Since the accelerating voltage satisfies $V_{acc} = V_c + V_b$, a maximum accelerating voltage of 97 kV is possible. However, this would require a collector depression of $V_b = 32$ kV, which may not be possible due to reflections of the slower electrons of the spent beam.

Taking into account the above specifications of the HVPS, two alternative cases of operating parameters have been assessed. The Low-Voltage High-Current (LVHC) case maintains the beam kinetic energy at 80 keV with a beam current of around 80 A. The High-Voltage Low-Current (HVLC) case increases the beam kinetic energy to 92 keV with a beam current of around 70 A. Assuming that the cathode block will be the same with the 1.5-MW TH1507U gyrotron, the second operating case relaxes the required emitter current density to 4.4 A/cm^2, compared to the 5 A/cm^2 of the LVHC case, offering a longer emitter-ring lifetime. Another important advantage of the HVLC case is the reduced space-charge depression, resulting from its lower beam current. For each of the two options, the value of the beam current is determined from the value of the beam energy, assuming a cavity electronic efficiency in the order of ~43 %, as in the case for TH1507U.

The magnetic compression—defined as the ratio of the magnetic field at the beam radius in the cavity to that at the emitter surface—for the superconducting magnets of the 1-MW TH1507 [1] and 1.5-MW TH1507U gyrotrons at W7-X is approximately 25. Given that the existing diode gun of the TH1507U tube has an emitter radius of ~50 mm, the electron beam radius in the cavity should be around 10 mm. This puts the candidate operating mode within the $TE_{28,p}$ mode series. The technological constraint for the TH1507U cavity Ohmic loading is currently set at 2.2 kW/cm^2 by the manufacturer (Thales, France) [3]. For the $TE_{28,p}$ series, the lowest-order mode satisfying this limit for 2-MW power at the gyrotron window is $TE_{28,14}$. However, with anticipated advancements in cooling systems and taking also into account that higher values of acceptable Ohmic loading are already reported in the literature [11], it is reasonable to expect that the limiting value for the Ohmic loading can increase to 2.5 kW/cm^2. As a result, the lowest-order mode within the $TE_{28,p}$ series that meets this requirement becomes $TE_{28,12}$.

To secure sufficient margin with respect to the desired 2-MW power at the gyrotron window, the targeted RF power at the cavity in nominal operation is set at 2.6 MW. Additionally, the adequate margin from the beam energy, where mode loss occurs (the point at which the operating mode begins losing power to competing cavity modes), has been set at 2 keV. The RF design of each cavity has been validated through multi-mode simulations of the beam-wave interaction using the European in-house code EURIDICE [12]. The electron beam parameters have been calculated with the commercial beam-optics code-package TRAK [13], based on the existing TH1507U diode gun where applicable, while assuming an estimated space-charge neutralization (i.e., a partial neutralization of the electron beam space charge by positive ions created from collisions between beam electrons and residual gas) of 70 % in long-pulse operation [3].

3. Continuous-wave operation

Building on the existing cavity of the 1.5-MW gyrotron at W7-X, two new cavities have been designed for the $TE_{28,12}$ mode to correspond to each of the two proposed operating parameter options (LVHC and HVLC). The midsection length has been optimized to balance the trade-off between electronic efficiency and the risk of more intense mode competition. Additionally, the cavity contour has been carefully refined to mitigate parasitic oscillations whenever possible [14] and to achieve a maximum wall loading of 2.5 kW/cm^2. Finally, the cavity radius has been increased from 22.83 mm to 25.16 mm to accommodate the higher power and ensure stable operation with the $TE_{28,12}$ mode at 140.35 GHz in the cold cavity.

3.1. LVHC operation

For the LVHC case the midsection length has been increased by ~2 mm compared to the baseline design of the 1.5-MW tube. This modification enhances the quality factor and the electronic efficiency. Based on the capabilities of the existing TH1507U diode gun in the existing magnetic field profile, the option of an electron velocity ratio $\alpha \sim 1.2$ with a beam radius of $R_b \sim 10.1$ mm has been selected, as other options led to suboptimal performance.

The simulated maximum output power achieved by the $TE_{28,12}$ mode at the LVHC option exceeds the 3-MW level. This is also considered to be parasitic-free operation, since no parasitic modes surpass 3 kW of power. Maintaining a secure 2-keV margin from mode loss, the design still allows the cavity power to reach 2.61 MW, at an electronic efficiency of 41.3 %. The results are shown in Fig. 1, whereas Table 1 summarizes the proposed nominal operating point and the calculated performance in long-pulse operation, incorporating the 2-keV mode-loss margin.

It should be noted that using the $TE_{28,12}$ mode presents a significant challenge due to the increased space-charge depression, which reaches 13.6 kV for the LVHC case, assuming $\alpha = 1.2$ at nominal operation. Such a high value can introduce difficulties during the gyrotron start-up phase when neutralization effects have yet to take effect (see Section 4.1).

3.2. HVLC operation

For the HVLC case, the midsection length has been reduced by ~2 mm compared to the baseline design. Longer cavities fail to achieve the targeted power level due to increased mode competition, whereas the shorter cavity has demonstrated superior performance. However, the use of the TH1507U diode gun at HVLC results in either a very high electron velocity ratio (>1.5) or a very large beam radius (>10.2 mm). Both configurations have been simulated and resulted in reduced performance. Achieving an optimal balance between these parameters in

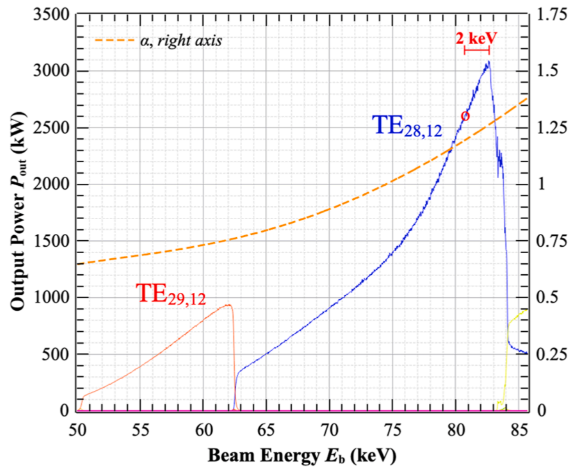

Fig. 1. Multi-mode simulation (59 modes) of the beam-wave interaction in long-pulse operation for the LVHC option, showing the power of different modes versus the beam energy. The operating point with a 2-keV margin from mode-loss is marked with the red circle. The beam current I_b and the electron velocity ratio α are also shown.

Table 1
Operating point and calculated performance for the LVHC option.

Electron kinetic energy	80.7 keV
Beam current	80.5 A
Magnetic field	5.554 T
Electron velocity ratio	1.2
Electron beam radius	10.1 mm
Accelerating voltage[1]	85 kV
Transverse velocity spread	4.7 %
Kinetic energy spread	0.04 %
Guiding center spread	3.6 %
RF power at the cavity	2.61 MW
Frequency	140.38 GHz
Ohmic losses[2]	65.5 kW
Maximum ohmic wall loading[2]	2.46 kW/cm^2
Electronic efficiency	41.3 %

[1] To account for a calculated partial space-charge neutralization of ~70 % during long-pulse operation.
[2] Assuming a correction factor of 1.8, w.r.t. ideal OFHC copper at room temperature.

CW operation requires modifications to the diode gun geometry. In particular, shifting the cathode block by - 2.2 mm along the gyrotron axis increases the anode-to-cathode distance, allowing the electron velocity ratio to approach the required 1.2 value with a beam radius of 10.1 mm. Therefore, this modified TH1507U diode has been used to determine the beam parameters for CW operation and the HVLC operating parameters.

With a 2-keV margin from mode loss, the RF power reaches the 2.6-MW goal. However, achieving this would require an accelerating voltage exceeding 95 kV, which is near the operational limit of the HVPS at W7-X. These results are shown in Fig. 2, and the proposed nominal operating point together with the calculated performance in long-pulse operation are summarized in Table 2. Note that the marginally lower electronic efficiency of the HVLC case is a consequence of the independent geometric optimization for each set of operating parameters, which results in slightly different beam-wave interaction conditions.

The space-charge depression value for the HVLC case is 11.4 kV, assuming $\alpha = 1.2$ during nominal operation. This value is significantly lower than the corresponding value for the previously discussed LVHC case due to the reduced beam current. However, this value still presents a challenge for diode start-ups, especially considering that the corresponding value for the $TE_{28,10}$ mode of the 1.5-MW gyrotron —and for most successfully operated gyrotrons— is usually below 10 kV.

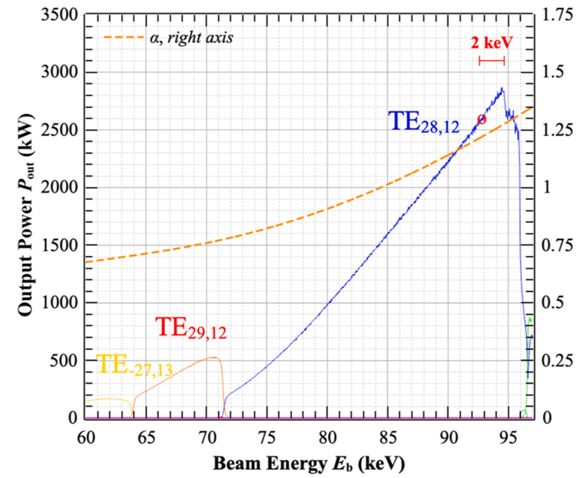

Fig. 2. Multi-mode simulation (49 modes) of the beam-wave interaction in long-pulse operation for the HVLC option, showing the power of different modes versus the beam energy. The operating point with a 2-keV margin from mode-loss is marked with the red circle. The beam current I_b and the electron velocity ratio α are also shown.

Table 2
Operating point and calculated performance for the HVLC option.

Electron kinetic energy	92.6 keV
Beam current	70.3 A
Magnetic field	5.6552 T
Electron velocity ratio	1.2
Electron beam radius	10.1 mm
Accelerating voltage[1]	95.8 kV
Transverse velocity spread	4.9 %
Kinetic energy spread	0.03 %
Guiding center spread	3.6 %
RF power at the cavity	2.6 MW
Frequency	140.40 GHz
Ohmic losses[2]	58.7 kW
Maximum ohmic wall loading[2]	2.49 kW/cm^2
Electronic efficiency	~40.7 %

Therefore, Section 4 provides a detailed investigation of the gyrotron start-up phase using a diode Magnetron Injection Gun (MIG).

4. Diode MIG start-ups

As previously noted, with the existing magnetic field profile, the TH1507U diode gun meets the electron beam requirements for the LVHC case in CW operation. By only axially shifting the cathode block, it meets the beam requirements for the HVLC case in CW operation. Therefore, the simulation of the gyrotron start-up for the LVHC case relies on the beam parameters calculated for the TH1507U diode gun, whereas for the HVLC case on the beam parameters of the slightly modified version of the TH1507U gun (see Section 3.2).

4.1. Simulation of the LVHC diode start-up

The diode start-up for the LVHC case with velocity ratio $\alpha = 1.2$ and beam radius $R_b = 10.1$ mm is examined using EURIDICE. Prior to the partial neutralization of the beam space-charge, the 10.1 mm beam radius results in a very high electron velocity ratio, causing significant voltage depression of approximately 17 kV. The start-up simulation for the 10.1 mm radius is shown in Fig. 3, where the time evolution of the space-charge depression is taken into account [15]. In particular, the shaded area represents the time range in the simulation during which the electron beam properties are progressively changed from those of a non-neutralized beam to a steady state of a 70 % space-charge

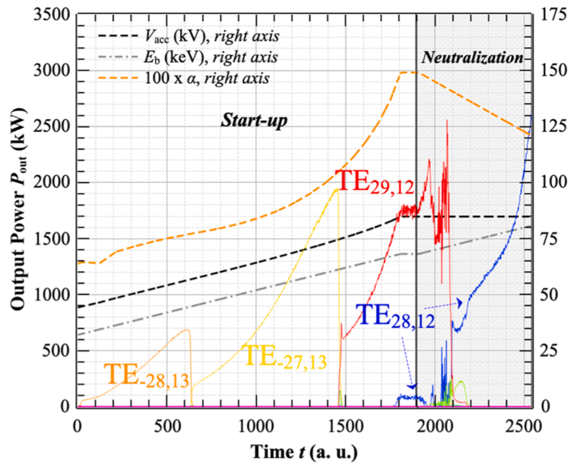

Fig. 3. Diode start-up for the LVHC case, based on the TH1507U diode gun for a 10.1 mm beam radius. The accelerating voltage V_{acc}, beam energy E_b and electron velocity ratio α are indicated on the right axis.

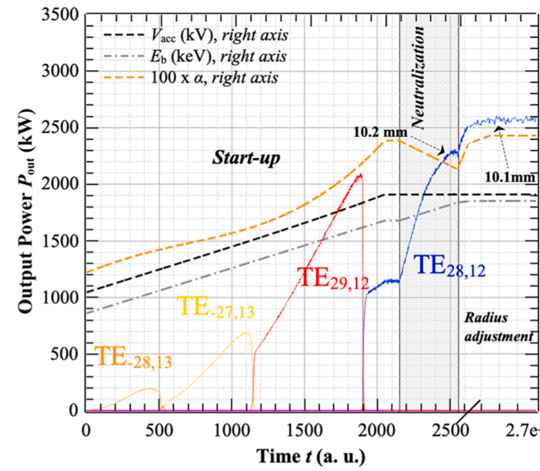

Fig. 4. Diode start-up for the HVLC case, based on a modified version of the TH1507U diode gun for an initial 10.2 mm beam radius. The accelerating voltage V_{acc}, beam energy E_b and electron velocity ratio α are indicated on the right axis.

neutralization.

As presented in Fig. 3, the large voltage depression prevents the excitation of the $TE_{28,12}$ mode before the neutralization of the space charge takes place. However, after the neutralization phase, the excited mode changes to the nominal $TE_{28,12}$. An alternative approach would involve operating with a larger beam radius to reduce the voltage depression. Once neutralization takes place, the beam radius can be reduced to the nominal value by adjusting the magnetic field at the emitter using the gun coils of the magnet. However, this option yields a similar outcome as that of Fig. 3. In summary, with both strategies the gyrotron will eventually reach the nominal mode $TE_{28,12}$ after operating with the competitor mode $TE_{29,12}$ for a time interval in the order of 100 ms, which is the typical time required for the space-charge neutralization to occur [16]. Of course, it is questionable whether the gyrotron can operate safely in the wrong mode for such a period without triggering any of the interlocks of the control system.

Given the concerns above with respect to the gyrotron start-up, the use of the counter-rotating $TE_{-28,12}$ mode as an alternative to $TE_{28,12}$ at the LVHC case has also been investigated. This mode requires a larger beam radius compared to $TE_{28,12}$, which reduces the space-charge depression. However, as the electron velocity ratio is also decreased at the larger beam radius, maintaining $\alpha = 1.2$ necessitates a change in the MIG geometry by an axial shift of the cathode block towards the anode. A cavity designed for this mode in CW operation also achieved 2.6 MW with a 2-keV margin from mode loss, yielding an electronic efficiency of 41.76 %. However, it was found that, despite the reduction in voltage depression (approximately 1 kV lower than the one for the $TE_{28,12}$ mode), an improved diode start-up scenario evading the gyrotron oscillating in a competing mode until the neutralization of the space charge is still not possible.

4.2. Simulation of the HVLC diode start-up

Regarding the diode start-up in the HVLC case, the initial investigation is conducted with an electron velocity ratio $\alpha = 1.2$ and a beam radius $R_b = 10.1$ mm, resulting in a voltage depression of approximately 12.3 kV. It turns out that, also in this case, the $TE_{28,12}$ mode cannot be excited during start-up to 95 kV. Consequently, the gyrotron must again tolerate operation in the incorrect mode $TE_{29,12}$ until neutralization occurs. However, operating with a larger beam radius, such as 10.2 mm, mitigates the space-charge depression issue. This more complex start-up scenario is shown in Fig. 4. Similarly to Fig. 3, we consider the space-charge neutralization effects to take place in the simulation within the shaded box. At an accelerating voltage of $V_{acc} = 95$ kV, this configuration yields a velocity ratio $\alpha = 1.2$ and a beam energy $E_b = 84$ keV.

Since the operating mode is excited at $V_{acc} = 95$ kV during start-up, the transition to the neutralized regime can occur with the larger beam radius and then shift to the nominal beam radius once the neutralization effect takes place. This strategy demonstrates that a diode start-up for the HVLC design case is, in principle, feasible while aligning with the power supply capabilities at W7-X. The required 95 kV would be achieved with cathode voltage $V_c = 65$ kV and body voltage $V_b = 30$ kV. This necessitates a large collector depression, yet still lower than the one already used in the TH1507U gyrotron, in terms of the ratio of V_b/V_{acc} [17].

5. Start-ups with a triode MIG design

Given the significant challenges posed by the diode start-up of the gyrotron in the presence of the large space-charge depression associated with the $TE_{28,12}$ mode, the possibility of a triode MIG was also investigated. This was done to showcase that a triode gun would eliminate the challenges with respect to the gyrotron start-up. (Of course, incorporating a triode gun would result in a significant deviation from the existing TH1507U layout; therefore, the associated risk should be assessed carefully.) A triode MIG was designed by using TRAK [13] and by making the least possible modifications to the existing TH1507U diode gun. This triode design is shown in Fig. 5. The main objective is to achieve an electron velocity ratio of approximately 1.2 at a 10.1 mm beam radius. To meet this requirement, the distance between the anode and the cathode was reduced by redesigning the anode contour and the anode was split into two electrodes: the modulation anode and the acceleration anode. The distances between these electrodes were carefully

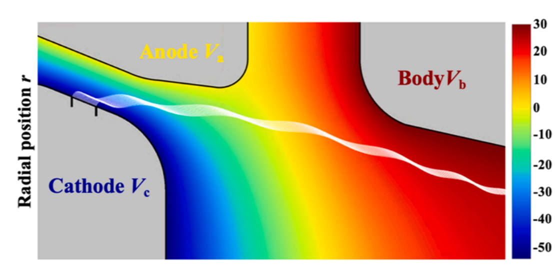

Fig. 5. Electric potential in the MIG region for the LVHC design case.

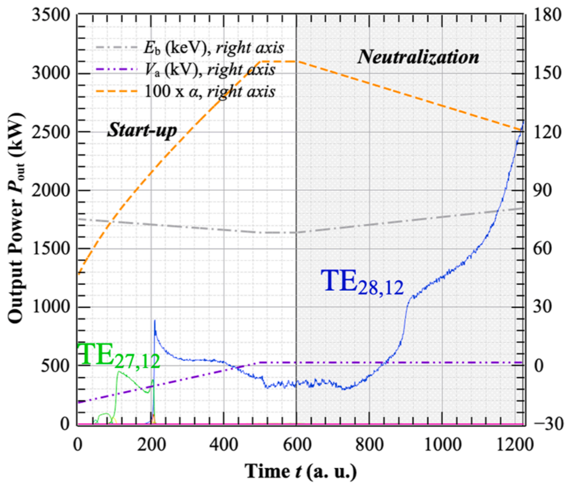

Fig. 6. Multi-mode simulation (59 modes) of the triode start-up for the LVHC design, based on the triode gun presented in Fig. 5. The electron velocity ratio *α*, beam energy E_b and modulation anode potential V_a are indicated on the right axis. The cathode potential V_c remains constant at its nominal value (−54.7 kV) throughout the entire process.

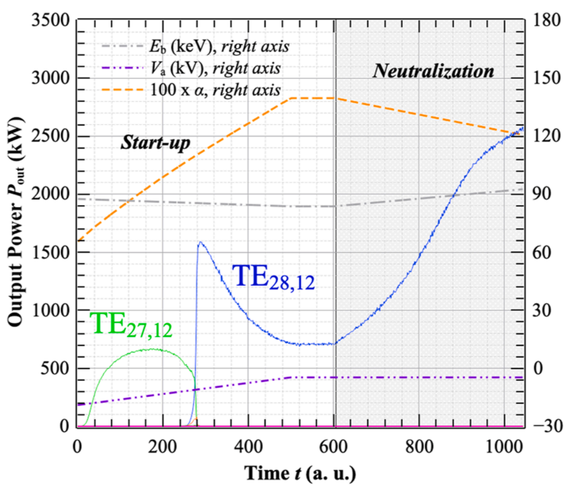

Fig. 7. Multi-mode simulation (49 modes) of the triode start-up for the HVLC design, based on the triode gun presented in Fig. 5. The electron velocity ratio *α*, beam energy E_b and modulation anode potential V_a are indicated on the right axis. The cathode potential V_c remains constant at its nominal value (−65 kV) throughout the entire process.

selected, considering the maximum potential that could be applied between them to avoid voltage breakdown. Since the main purpose of the triode design is to exhibit a successful gyrotron start-up, we used the same triode both for the LVHC and HVLC design cases.

Simplified triode start-up scenarios for the LVHC and HVLC operating cases are presented in Fig. 6 and Fig. 7, respectively, with the nominal potentials of the electrodes summarized in Table 3. The simulation strategy followed in both operating cases is to start with the cathode voltage and the body voltage at their nominal values ($t = 0$ a.u.), while the modulation-anode voltage is set to a value that leads to electron velocity ratio of ~0.5. Then the modulation-anode voltage is linearly increased until it reaches its nominal value ($t = 500$ a.u.) and neutralization effects start to take place ($t > 600$ a.u.). As expected, the increase of the electron velocity ratio is accompanied by a corresponding reduction of the beam's kinetic energy (7 keV for the LVHC case and 5 keV for the HVLC case), whereas during the neutralization phase the velocity ratio drops and the beam energy reaches its nominal value. By using the above-described strategy, the operating mode $TE_{28,12}$ is successfully excited during the start-up ($0 < t < 500$ a.u.) and then moves towards high-power operation after the neutralization takes place.

Table 3
Nominal potential of triode MIG electrodes.

	LVHC	HVLC
Cathode V_c	−54.7 kV	−65 kV
Anode V_a	1.6 kV	−4.7 kV
Body V_b	30 kV	31 kV

6. Summary and conclusions

For the scientific study of a 2-MW 140-GHz conventional cavity CW gyrotron for the W7-X stellarator, the mode $TE_{28,12}$ was selected for operation, with the goal of maximizing compatibility with the already existing 140-GHz 1.5-MW TH1507U gyrotron and the infrastructure at W7-X. The $TE_{28,12}$ mode was investigated under two alternative operating parameter cases, namely Low Voltage – High Current (80 keV – 80 A) and High Voltage – Low Current (92 keV – 70 A), each associated with a different cavity design. The multi-mode simulations corresponding to CW operation demonstrated that the operating mode can deliver the targeted power generated in the cavity, while ensuring a 2-keV margin from mode-loss, at both design cases. The maximum Ohmic wall loading is 2.5 kW/cm^2, assuming a correction factor of 1.8 with respect to ideal smooth OFHC copper at room temperature. It should be noted that this is a conservative value because it corresponds to an anticipated cavity wall temperature in the order of 350 °C in CW operation. If a correction factor of 1.6 is assumed instead, corresponding to a cavity wall temperature of the order of 250 °C that appears to be closer to reality [18], the maximum Ohmic wall loading in the proposed designs will be 2.2 kW/cm^2.

For the LVHC design, the existing electron gun of the TH1507U gyrotron can be used, as it is capable of providing the required beam parameters. For the HVLC design, a small modification of the TH1507U electron gun is necessary: the cathode block should be axially shifted away from the anode by around 2 mm.

The diode start-up simulations raise several challenges, due to the very large voltage depression associated with the $TE_{28,12}$ mode in a conventional cavity. For the LVHC case a diode start-up is only possible if temporary operation in a wrong mode is tolerated, until the neutralization effect allows the excitation of the mode $TE_{28,12}$. The same can be argued also for the HVLC design case. However, in the HVLC case a more sophisticated start-up scenario is also possible, which avoids gyrotron operation in a wrong mode during the neutralization phase. In particular, a larger-than-nominal electron beam radius of 10.2 mm can be used during start-up, and, after the neutralization of the beam space charge, the beam radius can be adjusted to the nominal value of 10.1 mm by changing the current of the gun coil of the magnet.

To overcome the challenges related to the diode start-ups, the triode-type configuration was also investigated. Based on the TH1507U diode gun, a triode gun, capable of providing the appropriate beam parameters for the two operating cases, was designed. With this triode, the operating mode was successfully excited both in the LVHC and HVLC cases, despite the very large voltage depression of the $TE_{28,12}$ mode. This would offer a more relaxed solution with respect to the gyrotron start-up, at the cost of increased complexity, of course.

CRediT authorship contribution statement

Emmanouil Deliprimis: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Zisis C. Ioannidis:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Konstantinos A. Avramidis:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Tobias Ruess: Validation, Investigation. **Stefan Illy:** Writing – review & editing. **John Jelonnek:** Conceptualization. **Manfred Thumm:** Writing – review & editing, Conceptualization. **Ioannis G. Tigelis:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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