Design Strategies for Second Harmonic Gyrotrons in Nuclear Fusion Applications

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***Abstract* — Gyrotrons are high-power microwave sources that play an important role in the heating of plasmas for magnetically confined thermonuclear fusion applications. This paper presents a comprehensive study of two potential strategies for operating high-power megawatt-class fusion gyrotrons at the second harmonic of the electron cyclotron frequency which requires only half of the gyrotron cavity magnetic field. The first approach focuses on a coaxial cavity design that effectively suppresses fundamental competing modes, making it a robust solution for second harmonic operation. The second strategy discusses the injection of an external locking signal. Therefore, a quasi-optical mode converter was designed and tested capable of handling both, co- and counter-rotating modes.**

***Keywords* — coaxial resonators, electron tubes, injection locking, gyrotrons, second harmonic operation**

I. Introduction

Nuclear fusion energy is emerging as a promising and clean alternative for the coming decades. Unlike fossil fuels, fusion does not emit greenhouse gases, making it a key player in combating climate change and reducing our dependence on non-renewable resources. Currently, over 80 magnetic confinement fusion experimental facilities, such as W7-x (Germany) and ASDEX Upgrade (Germany), are actively operating worldwide, highlighting the widespread effort to explore fusion's potential as a future energy source [1]. With ITER (France) under construction, the fusion community is now taking the next major technological step towards developing an industrial-scale power plant.

Magnetically confined thermonuclear fusion requires plasma to be heated to extremely high temperatures, necessitating the use of multiple plasma heating systems. Among these, electron cyclotron resonance heating (ECRH) is a promising technique, utilizing high-power continuous-wave (CW) RF sources with frequencies approximately ranging from 100 GHz to 200 GHz and above [2]. Compared to other non-inductive heating methods, the ECRH microwave sources can be positioned in a separate building, conserving valuable space within the tokamak building. The quasi-optical launching of the microwave beams only needs small openings on the blanket modules, and the beams can be easily redirected during transmission, simplifying the shielding of neutron streaming. As the microwave beams have small radii and can be further focused by mirrors, local deposition of the beam energy is possible, making the ECRH system essential in stabilizing the so-called neoclassical tearing mode.

Gyrotrons have proven to be highly efficient sources of coherent millimeter-wave radiation with long-pulse capabilities. Besides ECRH, gyrotrons are also used for plasma diagnostics, such as Collective Thomson Scattering. Gyrotrons operate based on the electron cyclotron resonance effect [3]. Thus, the generated microwave angular frequency ω is close to the electron cyclotron frequency Ω_c or higher harmonics, thereof. The interaction condition between electrons and the RF at any harmonic s can be expressed as

$$\omega = s\,\Omega_\mathrm{c} + k_\parallel\, v_\parallel\,, \qquad (1)$$

where $k_\parallel$ denotes the axial wave number and $v_\parallel$ the axial electron velocity. By these means, the physical dimensions of the resonant cavity are relatively large compared to the operating wavelength, which helps to keep the ohmic load on the cavity wall within acceptable limits ($\approx$ 2 kW/cm^2 or even higher) for the cooling circuits. Nevertheless, the ohmic load of the cavity walls is one of the main technological limiting factor as far as output power and efficiency are concerned.

For future power plant designs with high magnetic fields, there will be a demand for high-power gyrotrons at frequencies above 200 GHz. In harmonic operation, the operating frequency can be increased without an increase of the necessary magnetic field. This is anticipated to provoke a growing interest in harmonic high-power gyrotrons. When targeting the second harmonic $s = 2$, competition arises from fundamental cyclotron frequency modes $s = 1$ with low starting currents. For efficient harmonic interaction, the cavity design must either suppress the excitation of fundamental modes or the interaction with the desired second harmonic operating mode has to be driven by an external injection signal.

This paper theoretically investigates both approaches. In addition, a quasi-optical mode converter was designed, manufactured and measured in so-called "cold" tests for the injection locking method.

II. Suppression Scheme I: Coaxial Gyrotrons

It has been theoretically demonstrated that competing fundamental modes can be suppressed through the use of a coaxial cavity equipped with an impedance-corrugated insert [4]–[6]. In coaxial gyrotrons, the eigenvalue of the mode, and consequently its cutoff frequency and the cavity's diffractive quality factor, is determined by both the ratio of the outer to inner wall radii and the depth of the surface impedance corrugations on the inner conductor [7]. In this way, fundamental modes with caustic radii smaller than the operating mode can be suppressed.

If the corrugation depth of the insert is chosen between 0.4 and 0.6 times the free-space wavelength λ of the operating mode, the fundamental competing modes will effectively have a high surface impedance. Consequently, those fundamental competing modes have high starting currents. However, to ensure that the most dangerous competing modes are suppressed, the inner conductor must be thicker than in fundamental gyrotrons. This leads to an increased ohmic loading ρ on the inner conductor and is particularly problematic at high frequencies, since $\rho \propto f^{2.5}$ increases with frequency. In addition, the electron beam must be guided in close proximity to the inner conductor. This suppression mechanism can be further improved through a linear tapering of the corrugation depth, which allows a more precise adjustment of the surface impedance along the cavity axis, thereby improving the suppression of competing modes, as shown in [8]. Due to the improved suppression of competing modes, the radius of the inner conductor could be reduced from 8.0 to 7.5 mm without the fundamental modes prevailing.

Based on this approach, a 170 GHz $TE_{34,19}$-mode cavity was designed for second harmonic operation. The primary fundamental competing mode is the $TE_{17,11}$ at 85 GHz which needs to be suppressed. The new cavity design allows for an output power of 1.75 MW, as shown in Fig. 1, at a kinetic energy of the electrons of 80 keV entering the cavity, with a beam current of 100 A and a transversal to axial velocity ratio of 1.3. The interaction simulations were performed using the self-consistent multimode code EURIDICE [9].

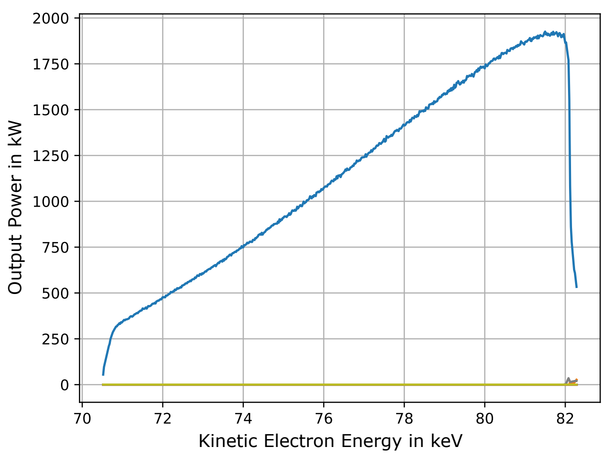

Fig. 1. Output Power of the second harmonic $TE_{34,19}$ operating mode

III. Suppression Scheme II: Injection Locking

Another approach to suppress the fundamental competing modes from overtaking the operation is to force the electrons to interact with the second harmonic operating mode, due to the injection of an external injection locking signal [10]. It has been shown that the required injection power follows the relation of Kurokawa, because it can be treated as an harmonic oscillator [11]–[13]. For fundamental operation, phase-locked gyrotron operation has already been demonstrated [14].

A. *Numerical Interaction Simulations*

To investigate whether second harmonic operation is possible in one of the existing KIT gyrotrons, injection-locking simulations were performed with the $TE_{32,09}$ mode hollow-cavity gyrotron presented in [15].

Interaction simulations are performed with EURIDICE [9], which is based on the classical beamlet approach and additionally simpleRick [16], [17], the KIT in-house particle-in-cell code. The simulation results confirm that the second harmonic operating modes prevail over the fundamental competing modes when a decent locking signal is injected at the cavity uptaper. However, the relation of Kurokawa also holds in that regard, consequently the injected power to phase-lock the operating mode has to be at least 300 kW for an output power of 1 MW to achieve a reasonable pull-in range of $\pm$50 MHz. To achieve this, a medium power 170 GHz 300 kW driver gyrotron was designed. The driver gyrotron was designed as a fundamental gyrotron with 35 % of interaction efficiency.

Considering that the frequency drop associated with the cavity expansion exceeds the lock-in range, an investigation was conducted to determine whether the gyrotron remains locked during cavity expansion due to the thermal heat load generated by ohmic losses in the cavity walls. The expanded cavity geometry was presented in [18] as a result of electrodynamic and thermomechanics multiphysics simulations.

During the PIC simulations the cavity radius is expanded gradually. The simulation results show, that a beating of the operating mode occurs as soon as the eigenfrequency of the cavity has dropped enough to leave the lock-in range. Those results indicate that CW operation of a second harmonic injection locked gyrotron will be challenging without frequency tuning of the master oscillator. Especially, due to the increased ohmic loading on the cavity walls caused by the injection signal. Although there are ways to tune the frequency of the master oscillator [19], the injection-locking approach remains rather complex compared to the coaxial gyrotron mentioned above.

To see, if the efficiency of the coaxial gyrotron can be improved by injection of an external signal, injection locking simulations of the $TE_{34,19}$ coaxial gyrotron were performed. Despite the fact that the electronic efficiency can be increased from 22.5 % to 25 %, this does not justify the additional expense for the injection locking approach. Nevertheless, a right and left hand rotating quasi-optical mode converter, so-called launcher antenna was designed, where co-rotating $TE_{+m,n}$ mode denotes the rotation in the same direction as the electrons and counter-rotating $TE_{-m,n}$ mode denotes the opposite rotation of the operating mode. This makes it possible to convert both, the injection signal into the intended operating mode and the output signal into a Gaussian-like beam in the window plane.

B. Design and Measurement of a Two-Rotational Quasi-Optical Mode Converter

The optimization method for mirror-line launchers, based on [20] has been successfully refined to improve the conversion efficiency of $TE_{\pm m,n}$ modes, particularly when the ratio of the caustic radius to the launcher radius is approximately 1/3. A mirror-line launcher has been designed for the $TE_{\pm 34,19}$ modes at 170 GHz, at a caustic-to-launcher radius ratio of 0.3232. The Gaussian mode content (GMC) of the RF beam at the launcher aperture is estimated to be 93.65 %.

Although the GMC could be enhanced to over 95 % using phase-correcting mirrors, these mirrors have complex contours and are highly sensitive to misalignment. Therefore, it is preferable to improve the launcher itself to generate Gaussian-like RF beams with a GMC exceeding 95 % at the aperture, allowing for the use of a simpler, non-correcting mirror system. Achieving a GMC greater than 95 % for the $TE_{\pm m,n}$ modes directly from the launcher, however, remains a significant technical challenge.

To verify the launcher design, an aluminum launcher was manufactured. Validating the quasi-optical output system is crucial prior to its installation in the gyrotron, as the components require manufacturing tolerances within a few micrometers for proper operation. This verification process, referred to as "cold measurements," is performed outside the tube and without the electron beam. To validate the quasi-optical output system, the relevant cavity modes are first excited using a quasi-optical mode generator [21]. Once the high-order rotating cavity modes are successfully excited, the quasi-optical output coupler undergoes thorough examination to confirm its performance. The quasi-optical mode generator consists of a rectangular-to-circular waveguide transition and a Potter horn, where the $TE_{1,0}$ fundamental rectangular waveguide mode is transformed into a Gaussian beam, $TEM_{0,0}$ mode. Teflon lenses and a quasi-parabolic mirror focus the beam on a perforated cavity wall with cutoff holes. The mode pattern is measured at the end of the cavity. The position of the quasi-parabolic mirror is optimised until the targeted operation mode is excited in the correct direction of rotation in the cavity.

The scalar correlation between the simulation and measurement is determined to be 96.6 % in the co-rotating case and 96.5 % in the counter-rotating case, indicating an excellent agreement as shown in figure 2 and figure 3. The interference patterns, which can be seen in the measurement results of the field profile, can be traced back to an excitation of small portions of the respective other direction of rotation in the mode generator.

IV. Conclusion

Two viable strategies for operating high-power MW-class fusion gyrotrons at the second harmonic of the cyclotron frequency are theoretically demonstrated. The first approach involves the use of a coaxial cavity, which offers a promising method for the suppression of fundamental competing modes. The second approach, based on injection locking is also possible, at least for short pulses. A co- and counter-rotating quasi-optical mode converter was successfully designed and tested. The experimental results showed excellent agreement with the simulations. While both approaches have their merits, the coaxial cavity method provides a simpler and more robust solution for practical implementation.

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Part of the simulations were performed on the EUROfusion High Performance Computer (Marconi-Fusion).

References

[1] IAEA, “World Survey of Fusion Devices 2022,” 2022.

[2] M. Thumm, “State-of-the-Art of High-Power Gyro-Devices and Free Electron Masers,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 41, no. 1, pp. 1–140, 1 Jan. 2020, ISSN: 1866-6892, 1866-6906. DOI: 10.1007/s10762-019-00631-y.

[3] V. Flyagin, A. Gaponov, I. Petelin, and V. Yulpatov, “The Gyrotron,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 25, no. 6, pp. 514–521, Jun. 1977. DOI: 10.1109/TMTT.1977.1129149.

[4] I. G. Chelis, K. A. Avramidis, D. V. Peponis, *et al.*, “High-Frequency MW-class Coaxial Gyrotron Cavities Operating at the Second Cyclotron Harmonic,” *IEEE Transactions on Electron Devices*, pp. 1–7, 2024. DOI: 10.1109/TED.2024.3356472.

[5] L. Feuerstein, A. Marek, C. Wu, S. Illy, M. Thumm, and J. Jelonnek, “Design of a Second Harmonic MW-Level Coaxial Gyrotron Cavity,” in *2023 24th International Vacuum Electronics Conference (IVEC)*, 2023, pp. 1–2. DOI: 10.1109/IVEC56627.2023.10156958.

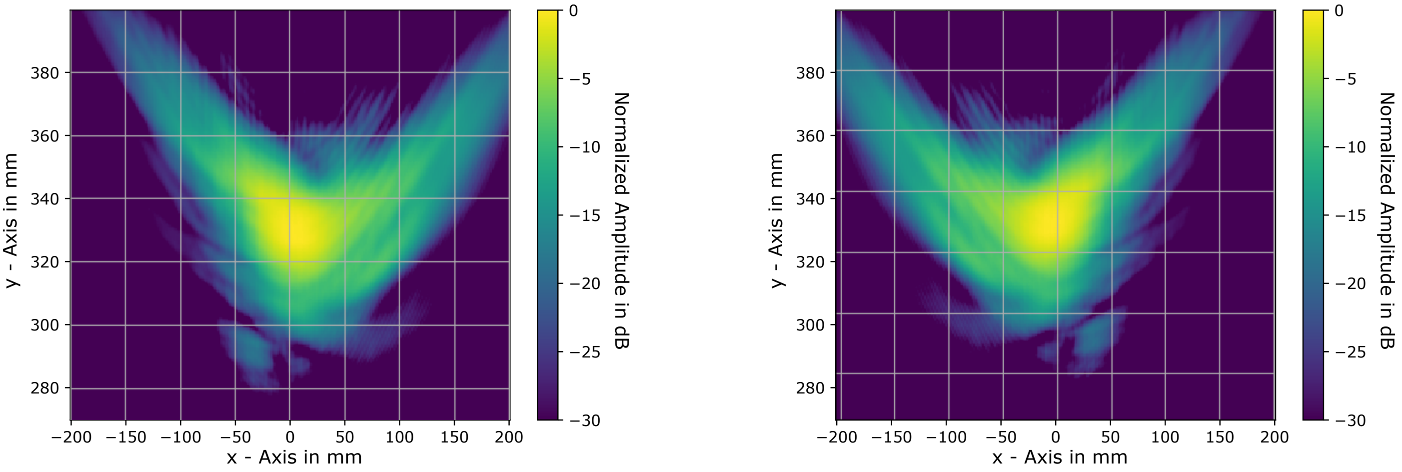
[6] D. V. Peponis, K. A. Avramidis, I. G. Chelis, *et al.*, “Design of MW-Class Coaxial Gyrotron Cavities With Mode-Converting Corrugation Operating at the Second Cyclotron Harmonic,” *IEEE Transactions on Electron Devices*, vol. 70, no. 12, pp. 6587–6593, Dec. 2023. DOI: 10.1109/TED.2023.3326431.

[7] C. Iatrou, “Mode selective properties of coaxial gyrotron resonators,” *IEEE Transactions on Plasma Science*, vol. 24, no. 3, pp. 596–605, 3 Jun. 1996. DOI: 10.1109/27.532942.

[8] L. Feuerstein, V. I. Shcherbinin, K. A. Avramidis, *et al.*, “MW Level 280 GHz 2nd Harmonic Coaxial Gyrotron Cavity with Variable Corrugation Depth,” in *2024 Joint International Vacuum Electronics Conference and International Vacuum Electron Sources Conference (IVEC + IVESC)*, Monterey, CA, USA: IEEE, 2024, pp. 01–02. DOI: 10.1109/IVECIVESC60838.2024.10694886.

[9] K. A. Avramides, I. G. Pagonakis, C. T. Iatrou, and J. L. Vomvoridis, “EURIDICE: A code-package for gyrotron interaction simulations and cavity design,” *EPJ Web of Conferences*, vol. 32, p. 04 016, 2012. DOI: 10.1051/epjconf/20123204016.

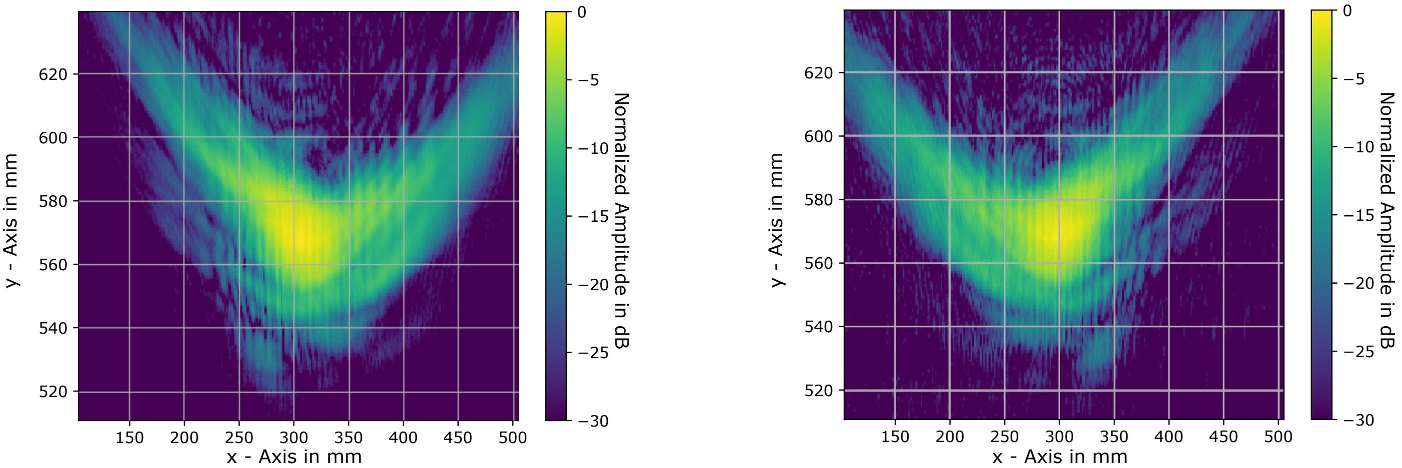
[10] G. G. Denisov, I. V. Zotova, I. V. Zheleznov, *et al.*, “Phase-Locking of Second-Harmonic Gyrotrons for Providing MW-Level Output Power,” *IEEE Transactions on Electron Devices*, pp. 1–5, 2021. DOI: 10.1109/TED.2021.3134187.



(a) Co-Rotating $TE_{+34,19}$ as launcher input

(b) Counter-Rotating $TE_{-34,19}$ as launcher input

Fig. 2. Simulation of the field profile in the plane of the first mirror



(a) Co-Rotating $TE_{+34,19}$ as launcher input

(b) Counter-Rotating $TE_{-34,19}$ as launcher input

Fig. 3. Measurement of the field profile in the plane of the first mirror

[11] K. Kurokawa, "Injection locking of microwave solid-state oscillators," *Proceedings of the IEEE*, vol. 61, no. 10, pp. 1386–1410, Oct. 1973. DOI: 10.1109/PROC.1973.9293.

[12] J. Jelonnek, A. Grudiev, and K. Schunemann, "Rigorous computation of time-dependent electromagnetic fields in gyrotron cavities excited by internal sources," *IEEE Transactions on Plasma Science*, vol. 27, no. 2, pp. 374–383, 1999. DOI: 10.1109/27.772264.

[13] P. Brücker, K. A. Avramidis, A. Marek, M. Thumm, and J. Jelonnek, "Theoretical Investigation on Injection Locking of the EU 170 GHz 2 MW TE34,19-Mode Coaxial-Cavity Gyrotron," in *2021 46th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, Aug. 2021, pp. 1–2. DOI: 10 . 1109 / IRMMW - THz50926.2021.9567563.

[14] A. N. Kuftin, G. G. Denisov, A. V. Chirkov, *et al.*, "First Demonstration of Frequency-Locked Operation of a 170 GHz/1 MW Gyrotron," *IEEE Electron Device Letters*, vol. 44, no. 9, pp. 1563–1566, Sep. 2023. DOI: 10.1109/LED.2023.3294755.

[15] Z. C. Ioannidis, T. Rzesnicki, F. Albajar, *et al.*, "CW Experiments With the EU 1-MW, 170-GHz Industrial Prototype Gyrotron for ITER at KIT," *IEEE Transactions on Electron Devices*, vol. 64, no. 9, pp. 3885–3892, Sep. 2017. DOI: 10.1109/TED.2017.2730242.

[16] A. Marek, K. A. Avramidis, L. Feuerstein, *et al.*, "Time-Domain Simulation of Helical Gyro-TWTs With Coupled Modes Method and 3-D Particle Beam," *IEEE Transactions on Electron Devices*, vol. 69, no. 8, pp. 4546–4552, Aug. 2022. DOI: 10.1109/TED.2022.3182292.

[17] L. Feuerstein, A. Marek, K. A. Avramidis, S. Illy, C. Wu, and J. Jelonnek, "Validation of a New Fast-Time Scale Code for Advanced Simulations of Gyrotron Cavities," in *2022 14th German Microwave Conference (GeMiC)*, May 2022, pp. 144–147.

[18] K. A. Avramidis, A. Bertinetti, F. Albajar, *et al.*, "Numerical Studies on the Influence of Cavity Thermal Expansion on the Performance of a High-Power Gyrotron," *IEEE Transactions on Electron Devices*, vol. 65, no. 6, pp. 2308–2315, Jun. 2018. DOI: 10.1109/TED.2017.2782365.

[19] A. N. Kuftin, G. Y. Golubiatnikov, V. A. Vilkov, *et al.*, "Experimental Study of Extended Operating Zone of a 170-GHz/1-MW Gyrotron Locked by a Narrowband External Signal," *IEEE Transactions on Electron Devices*, vol. 71, no. 11, pp. 7061–7065, Nov. 2024. DOI: 10.1109/TED.2024.3457568.

[20] J. Jin, M. Thumm, B. Piosczyk, and T. Rzesnicki, "Theoretical investigation of an advanced launcher for a 2-MW 170-GHz TE 34,19 coaxial cavity gyrotron," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 3, pp. 1139–1145, 2006. DOI: 10.1109/TMTT.2005.864114.

[21] N. L. Alexandrov, G. G. Denisov, D. R. Whaley, and M. Q. Tran, "Low-power excitation of gyrotron-type modes in a cylindrical waveguide using quasi-optical techniques," *International Journal of Electronics*, vol. 79, no. 2, pp. 215–226, Aug. 1995. DOI: 10.1080/00207219508926263.