TE and TM Mode Competition in Subterahertz Gyrotron Using Axis-encircling Electron Beam

Tien-Fu Yang[1*], Hsin-Yu Yao[2], Chia-Chuan Chang[1], Chao-Hai Du[3], Feng Zhang[3], and Tsun-Hsu Chang[1]

[1]*Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan*
[2]*Department of Physics, National Chung Cheng University, Chiayi 621301, Taiwan*
[3]*School of Electronics, Peking University, Beijing 100871, China*
**email of Corresponding author: yang168@gapp.nthu.edu.tw.*

Abstract: This work demonstrates that an axis-encircling electron beam with high mode selectivity is adapted to preclude most parasitic modes and makes the TM_{12}-mode oscillation in an open-cavity-type gyrotron system feasible. Considering the modes excited at the fundamental cyclotron harmonic, the TE_{12} mode remains the only competitor to the targeted TM_{12} mode, however, it will be effectively suppressed by the axial velocity spread. Operating with 70 kV beam voltage and 1 A beam current, the output power of the TM_{12} mode may reach the several-kilowatt level, verified by both nonlinear frequency-domain and time-domain simulations. Nonetheless, as the modes at high cyclotron harmonics are included, the second-harmonic TE_{24} mode and the third-harmonic TE_{36} mode would potentially hazard the proposed TM_{12}-mode operation. Even so, the particle-in-cell CST simulation results still show a tunable window of the TM_{12} mode. This work manifests the importance of considering the competition from TM modes in the designs of gyrotron devices, especially for the cases employing axis-encircling electron beams.

Keywords: Electron Cyclotron Maser, Gyrotron Oscillator, Intrinsic Resonance, Absolute Instability

1. Introduction

In gyrotrons, strong modulation on the electron beam under coherent beam-wave interaction leads to electron bunching in phase space either azimuthally or axially. The near-cutoff operation for TM mode minimizes the transverse electric field so that the azimuthal bunching caused by the relativistic Doppler shift can be suppressed. Nevertheless, TM modes exhibit an additional axial electric field (E_z), expected to trigger both two bunching processes. Therefore, the traditional gyrotron community believes that TM modes are susceptible to significant bunching competition and substantial power degradation due to the large velocity spread modulated by E_z.

Several recent theoretical studies on TM-mode gyrotrons [1] have been devoted to studying the underlying mechanisms and assessing the feasibility of implementation. However, the current understanding of the feasibility of TM-mode gyrotron still remains incomplete, as it lacks clear evidence derived from a more realistic platform. Such a platform should enable the exploration of mode competition among all parasitic oscillations, either TE or TM modes at fundamental or higher-order harmonics, and simultaneously offer the flexibility to adjust the magnetic field and beam parameters. This study aims to provide a theoretical evaluation of the TM-mode gyrotron system developed at Peking University using the axis-encircling electron beam [2]. The particle-in-cell (PIC) solver of Computer Simulation Technology (CST) is employed to study the mode competitions in the time domain.

2. Technical Work

The coupling strength for the $\mathrm{TM}_{12}^{(1)}$ is at the same level as that of the $\mathrm{TE}_{24}^{(2)}$ mode, as Fig. 1(a) shows. The comparable beam-wave coupling strength positions the $\mathrm{TE}_{24}^{(2)}$ mode as a robust competitor in the desired tuning range. However, compared with the $\mathrm{TM}_{12}^{(1)}$ mode, the $\mathrm{TE}_{24}^{(2)}$ mode is operated at a relatively far-cutoff region (checked by the dispersion curves), which may weaken its oscillation in the nonlinear regime. The secondary competitor is the $\mathrm{TE}_{36}^{(3)}$ mode. The near-cutoff operation might enable the $\mathrm{TE}_{36}^{(3)}$ mode to dominate over the tri-mode competition process with $\mathrm{TM}_{12}^{(1)}$ and $\mathrm{TE}_{24}^{(2)}$. As for the $\mathrm{TM}_{47}^{(4)}$ and $\mathrm{TE}_{48}^{(4)}$ modes, since their mode coupling strengths are two orders of magnitude smaller than that of the $\mathrm{TM}_{12}^{(1)}$ or $\mathrm{TE}_{24}^{(2)}$ modes, these two are expected to play no essential role during the excitation.

Figure 1(b) plots the start-oscillation currents of the targeted $\mathrm{TM}_{12}^{(1)}$ mode and the other two parasitic modes. 20% axial velocity spread is considered. I_{st} for the $\mathrm{TE}_{48}^{(4)}$ mode and the $\mathrm{TM}_{47}^{(4)}$ mode are outside the display range and therefore not shown. Since the beam-wave coupling strength of the $\mathrm{TE}_{24}^{(2)}$ is comparable with that of the $\mathrm{TM}_{12}^{(1)}$ mode, the $\mathrm{TE}_{24}^{(2)}$ can exhibit a smaller starting current at lower-B_0 region, owing to its more near-cutoff operation. However, as B_0 is tuned up to around 85.5 kG, the $\mathrm{TM}_{12}^{(1)}$ mode with smaller starting current is expected to take the lead in oscillation. Unfortunately, the $\mathrm{TE}_{36}^{(3)}$ mode simultaneously emerges with an even smaller I_{st}. Nonetheless, a mode with a smaller starting current is not promised to win the whole mode competition, especially when multiple modes are allowed to excite at the same time. Consequences of the mode competition can only be determined using multimode time-domain simulations or a direct examination of proof-of-principle experiments.

A total of 218 modes are taken into consideration at the wave ports, facilitating the excitation and extraction of the oscillations from competitive modes in PIC-CST simulations. Figures 1(c), 1(d), and 1(e) show the results at three characteristic B-fields, indicated by arrows in Fig. 1(b). The results demonstrate that $\mathrm{TM}_{12}^{(1)}$ dominates the mode competitions in a specific region, which implies the feasibility of TM-mode gyrotron.

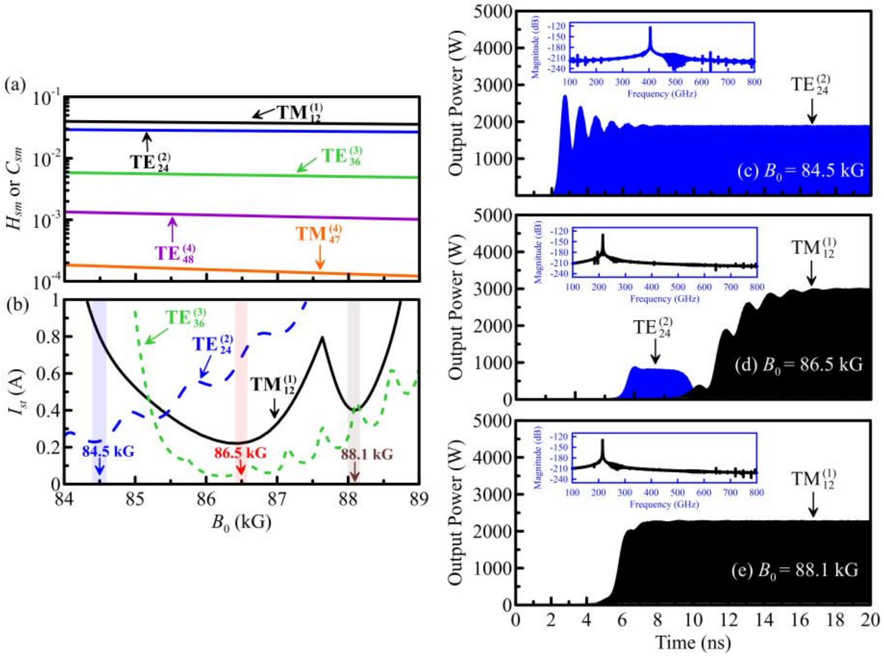

Fig. 1. (a) Coupling strengths of the potential parasitic modes with high cyclotron harmonic interaction. (b) I_{st} as functions of B_0 for all the parasitic modes allowed for high-harmonic operations. The axial velocity spread of 20% is considered. (c), (d), and (e) are CST-PIC simulations at B_0 = 84.5 kG, 86.5 kG, and 88.1 kG, respectively. The Fourier spectrum of each primary signal is shown in the corresponding inset. The beam parameters employed in the simulations are V_b = 70 kV, I_b = 1 A, $r_c = r_L/3$, and α = 1.5 with 20% axial velocity spread for all of the cases.

3. Conclusions

The feasibility of TM-mode gyrotrons with the classical open-cavity configuration is demonstrated, using the axis-encircling beam developed at Peking University. The comparative study on the beam-wave coupling strengths explains why in typical gyrotron systems, the output of TM modes is hard to detect. However, with the assistance of the axis-encircling beam, the number of parasitic modes can be largely reduced, indicating a chance to implement a TM-mode gyrotron. Mimicking real-world scenarios, our simulations using the PIC solver of CST Studio serve as a robust evaluation of the feasibility of the proof-of-principle experiment. The $\mathrm{TM}_{12}^{(1)}$ mode is found to suppress all the TE parasitic modes with the output power of at least several kilowatts This demonstration refreshes the traditional understanding that TM-mode is not feasible in the gyrotron system operating at typical beam voltage (~70 kV) and beam current (~1 A). Last but not least, the evidence of TM-mode oscillation shown in this work suggests that a comprehensive understanding of the mode competition in gyrotron devices should not directly exclude TM modes from the discussion. In other words, the discovery in this article may indicate that when optimizing TE-mode gyrotron with overmoded waveguide structures injected by large-orbit electron beams, careful consideration should be given to the potential presence of competing TM parasitic modes.

References

[1] H.-Y. Yao, C.-H. Wei, and T.-H. Chang, “Nonlinear and self-consistent single-mode formulation for TM-mode gyrotrons,” Phys. Rev. E 104, 065205 (2021).

[2] V. L. Bratman, Yu. K. Kalynov, and V. N. Manuilov, “Large-Orbit Gyrotron Operation in the Terahertz Frequency Range,” Phys. Rev. Lett. 102, 245101 (2009).