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

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Abstract

For a long time, most gyrotron oscillators have avoided utilizing TM modes because of the concerns about strong bunching competition and relatively weak beam-wave coupling. However, 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, where all parasitic TE-mode oscillations are fully suppressed. 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. Currently, the proposed system is being constructed at Peking University, Beijing, with preliminary tests supporting the findings of this study.

Background and Importance

Gyrotrons, efficient sources of millimeter and terahertz waves, rely on stimulated cyclotron emission from relativistic electron beams, which undergo coherent beam-wave interaction leading to electron bunching in phase space either azimuthally or axially[1]. The competition between two bunching mechanisms results in low interaction efficiency. Near-cutoff operation is commonly used to address this issue, reducing axial Lorentz force for TE modes and minimizing transverse electric fields for TM modes. However, TM modes may still experience significant bunching competition due to the axial electric field (E_z), leading to potential power degradation. As a result, the traditional gyrotron community usually believes that TM modes are not suitable for gyrotron operation and therefore usually excludes TM modes from analyses.

Several recent theoretical studies on TM-mode gyrotrons have been devoted to studying the underlying mechanisms and assessing the feasibility of implementation. However, they lack evidence from realistic platforms, necessitating a comprehensive evaluation. 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 focuses on a TM-mode gyrotron system developed at Peking University, utilizing a magnetic cusp gun for high mode-selectivity. Single-mode particle-tracing simulation and multimode time-dependent simulations using a PIC solver are conducted to assess TM-mode performance in the nonlinear region. The study underscores the importance of considering TM mode, particularly in harmonic TE-mode gyrotrons using axis-encircling electron beams, due to comparable mode-coupling strengths.

The importance of considering TM mode has been emphasized, especially in the context of harmonic TE-mode gyrotrons using the axis-encircling electron beam, because the mode-coupling strength of an s+1-harmonic TE-mode and that of an s-harmonic TM-mode are comparable.

Comparative Study on Modal Coupling Strengths

The beam-wave coupling strength, H_{sm} for TE [1] and C_{sm} for TM [2], are

$$H_{sm} = J_{s-m}^2\left(k_{mn}r_c\right)J_s'^2\left(k_{mn}r_L\right)$$

$$C_{sm} = J_{s-m}^2\left(k_{mn}r_c\right)J_s^2\left(k_{mn}r_L\right)$$

The coupling strength under the axis-encircling condition ($r_c = 0$) may be written as

$$H_{mm}^{\mathrm{LOB}} = J_s'^2\left[f\left(m,q,\alpha,V_b\right)\right],\quad f\left(m,q,\alpha,V_b\right)=\frac{m}{q}\alpha\left\{\left(\alpha^2+1\right)\left[1-\left(1+V_b/U_0\right)^{-2}\right]^{-1}-1\right\}^{-1/2}$$

$$C_{mm}^{\mathrm{LOB}} = J_s^2\left[f\left(m,q,\alpha,V_b\right)\right]$$

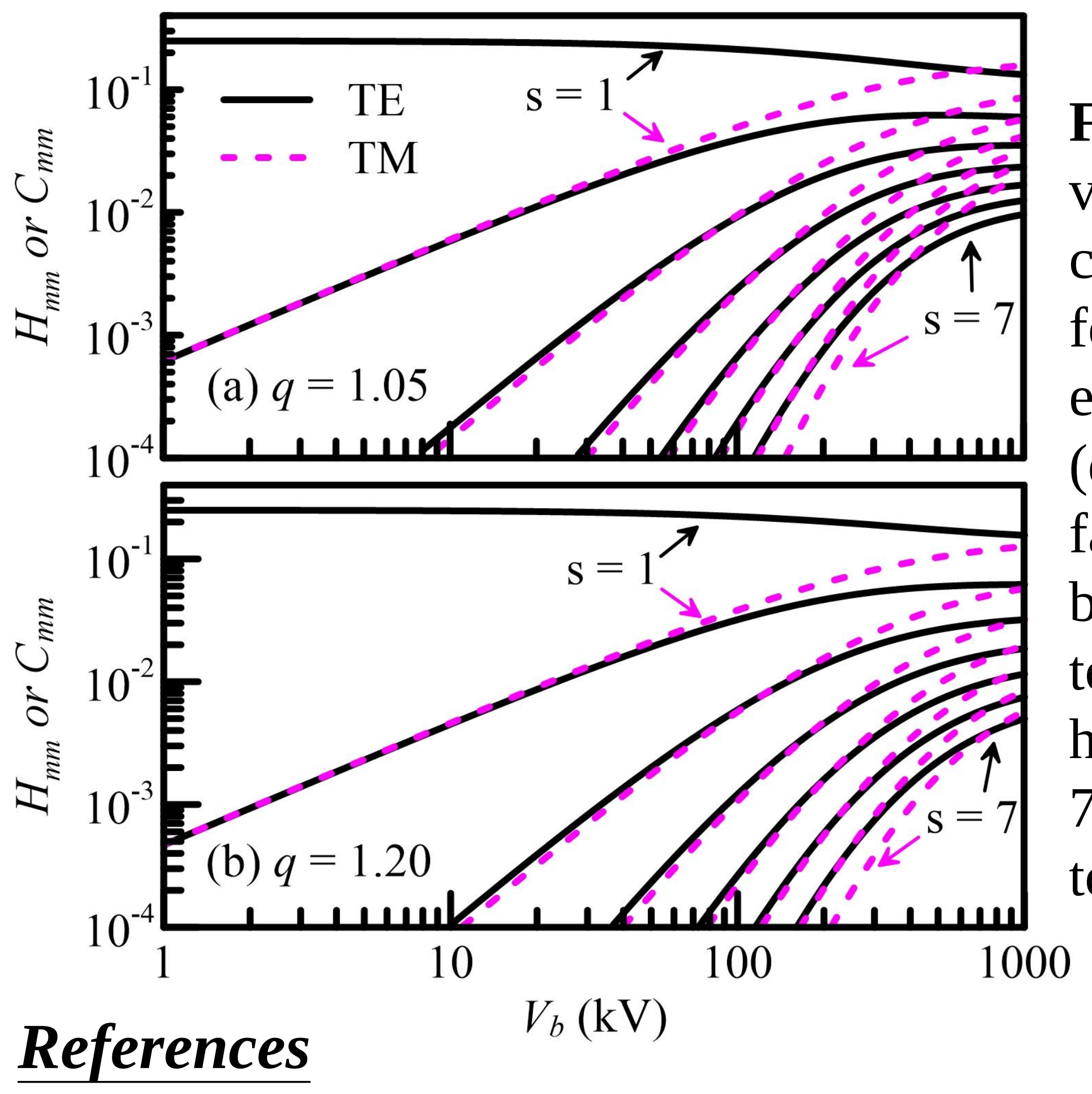

Fig. 1. Beam-wave coupling strengths versus beam voltage V_b under different cyclotron harmonic numbers s. We only focus on the mode with m=s due to the employment of LOB. The solid black (dotted pink) lines indicate the coupling factors of TE (TM) modes. Moreover, in both (a) and (b), for the curves from the top to the bottom, the corresponding harmonic number increases from s = 1 to 7. The pitch factor α (beam's transverse-to-axial velocity ratio) is 1.5.

References

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[3] T. F. Yang, H. Y. Yao, C. C. Chang, C. H. Du, F. Zhang, and T. H. Chang, "TE- and TM-Mode Competition in Subterahertz Gyrotron Using Axis-Encircling Electron Beam," *IEEE Trans. Electron Devices* 71 (1), 815 (2024).

Design and Self-Consistent, Start-Oscillation Analyses

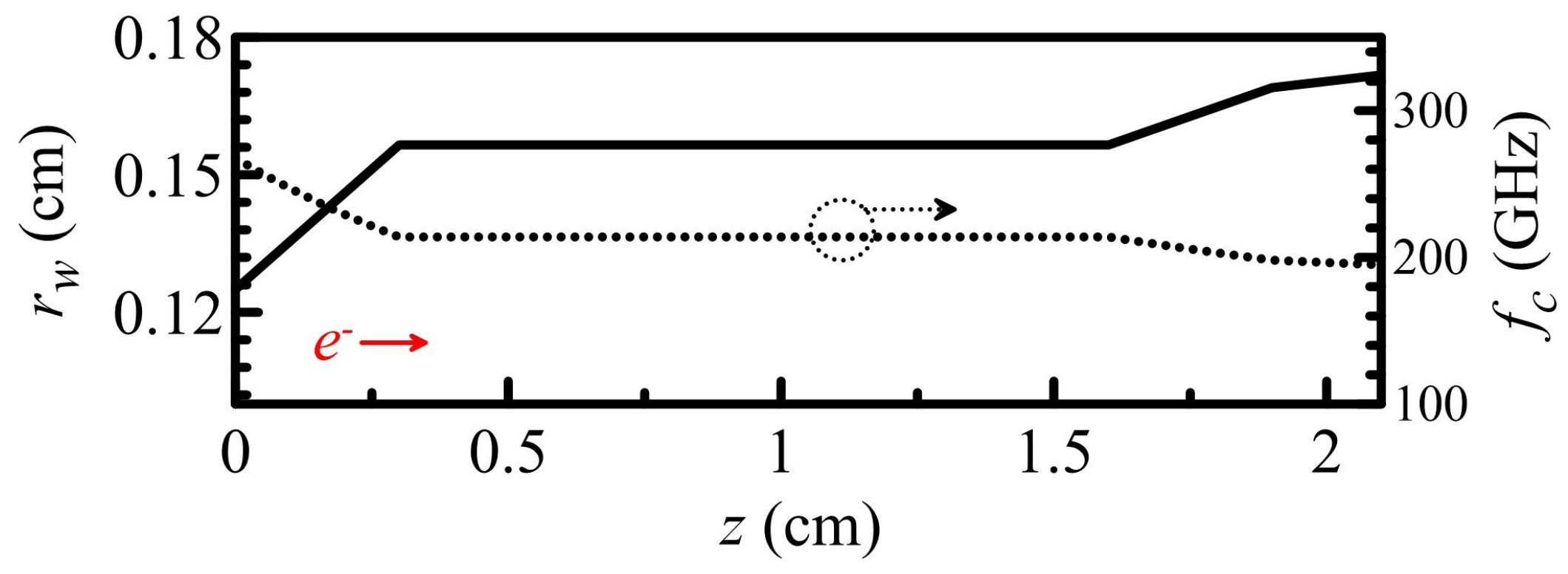

Fig. 2. Geometry of the designed tube (solid curve) and the corresponding cutoff frequencies of the TM12 mode (dotted curve) at each point.

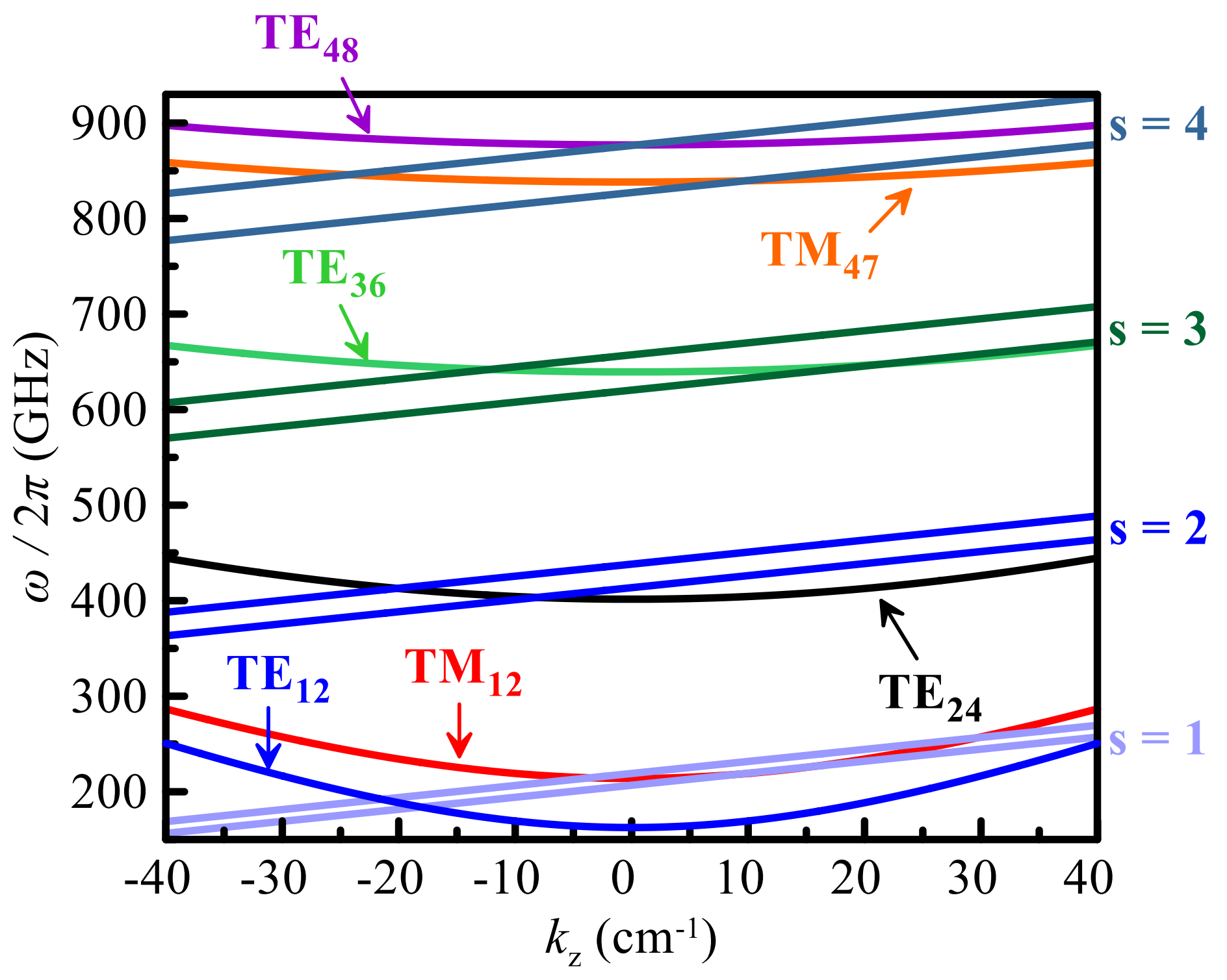

Fig. 3. Dispersion analyses of nearby possibly excited modes

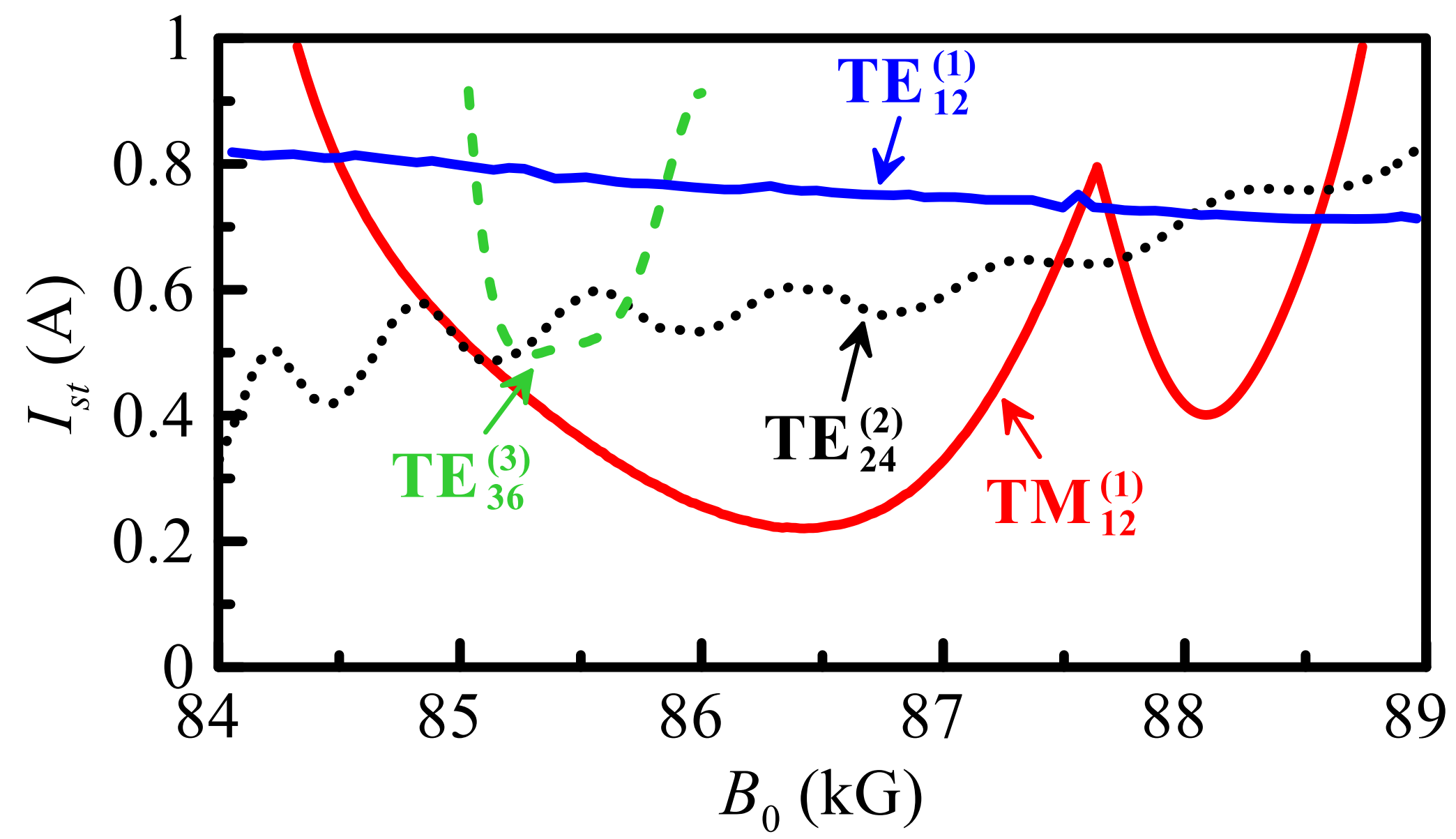

Fig. 4. I_{st} as functions of B_0 for all the parasitic modes allowed for operations. The axial velocity spread of 20% is considered.

Multi-mode Particle-in-cell Simulations

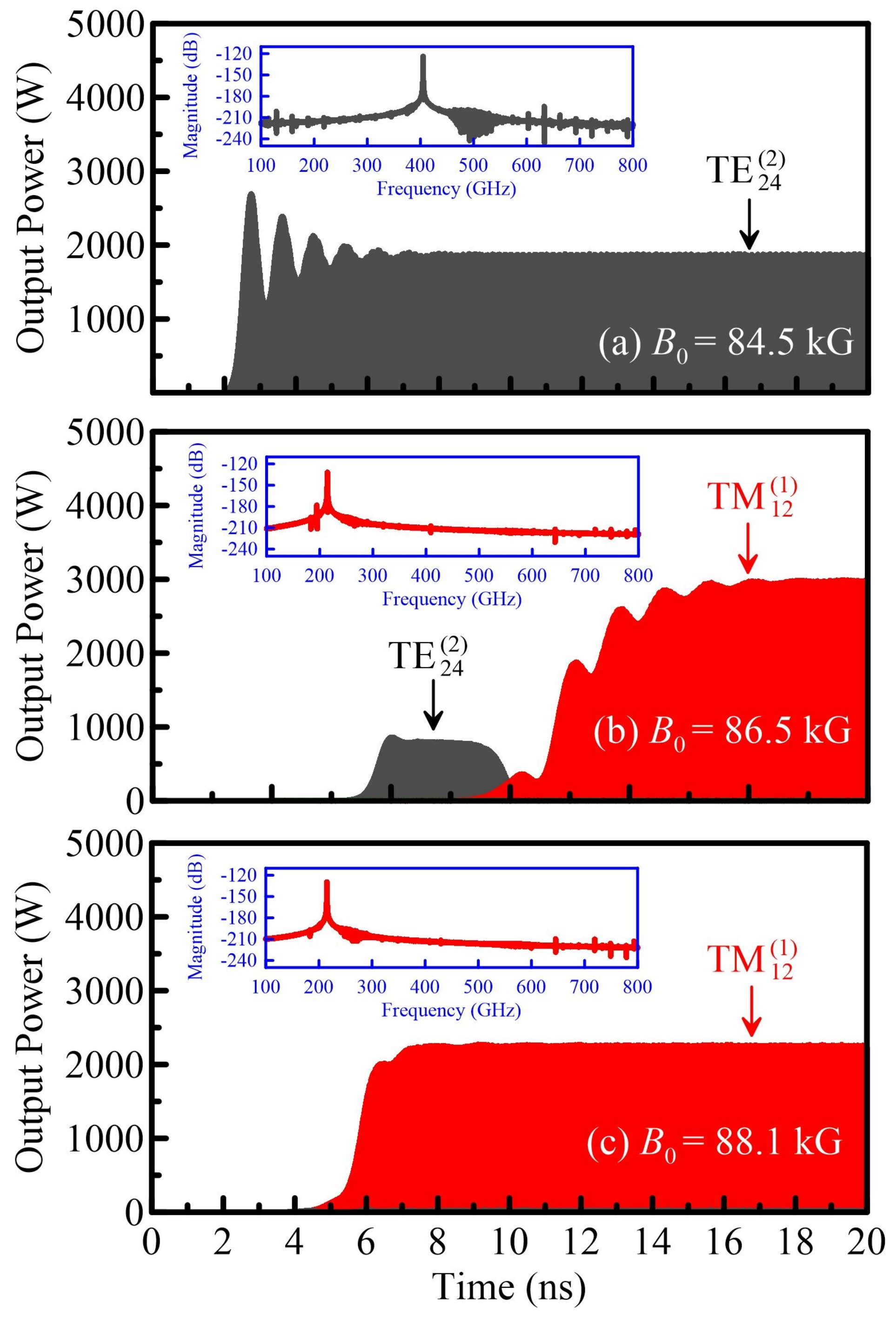

Fig. 5. CST-PIC simulations at B_0 of (a) 84.5 kG, (b) 86.5 kG, and (c) 88.1 kG. The Fourier spectrum of each primary signal is shown in the corresponding inset. The beam parameters employed in the simulations are V_b = 70 kV, I_b = 1 A, and α = 1.5 with 20% axial velocity spread for all of the cases.