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Start-Up Condition Analysis and Mode Selection Optimization in Gyrotron Operation

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Abstract – **This work examines the critical start-up conditions and strategies for managing mode competition in a 140 GHz gyrotron operating in the $TE_{10,4}$ mode. A MATLAB simulation was employed to determine the optimal electron beam position for maximizing the coupling coefficient. Calculations indicated that a magnetic flux density of 5.68 Tesla was required to initiate oscillation in the desired mode. By carefully selecting the start oscillation current, we were able to suppress competing modes effectively, ensuring excitation in the target $TE_{10,4}$ mode. Mode competition is a critical issue in gyrotron operation, as the presence of undesired modes can reduce efficiency and stability. In our approach, tuning the magnetic field strength and start oscillation current allowed for precise control over mode selection, reducing the risk of mode hopping or interference from other modes. These findings contribute to a better understanding of mode selection mechanisms in high-frequency gyrotrons and provide a foundation for improving operational stability and efficiency in devices requiring high-purity mode excitation, such as in high-precision advanced material processing in industrial applications, plasma diagnostics, electron cyclotron resonance heating (ECRH) and scientific research applications. The insights from this study could guide future design strategies for gyrotrons operating in similar high-frequency regimes.**

Keywords – **High-power microwave devices, Gyrotron, Start-up conditions, Mode competition, Electron beam positioning**

I. Introduction

Microwave tubes remain the leading technology for generating high-power electromagnetic (EM) waves in the microwave to millimeter wavelength spectrum, as their solid-state counterparts have yet to match their power capabilities in these frequency bands. Their significance was especially highlighted during World War II, where the demand for high-power, high-frequency devices spurred extensive research and development. This focus not only demonstrated the critical role of microwave tubes in communication, radar, and other military applications but also laid the groundwork for continued advancements in the field. The combination of these early demands with subsequent technological advancements—particularly in superconducting magnet technology—has led to the emergence of a new class of high-frequency devices called fast-wave microwave devices. Among these devices, the gyromonotron (also known as the gyrotron), the gyro-klystron, and the gyro traveling-wave tube (gyro-TWT) are prominent examples that have expanded the capabilities of high-frequency power generation [1]-[4].

The gyrotron, or gyromonotron, operates as a high-efficiency, fast-wave electron beam oscillator and can deliver megawatts of EM power in the millimeter and sub-millimeter frequency bands. Gyrotrons have become indispensable tools in various industrial and scientific applications due to their ability to generate high-power electromagnetic waves in the millimeter and sub-millimeter wavelength ranges. Beyond their traditional roles in radar systems, communication, and plasma diagnostics, gyrotrons are increasingly contributing to cutting-edge fields such as fusion research and additive manufacturing [1-6].

In fusion research, gyrotrons serve as critical components for Electron Cyclotron Resonance Heating (ECRH) systems, where they deliver precise and high-power RF energy to stabilize and heat plasma. This capability is vital for achieving and maintaining the conditions necessary for sustained nuclear fusion reactions in experimental setups like ITER (International Thermonuclear Experimental Reactor) [1-6].

Similarly, in additive manufacturing, gyrotrons offer innovative solutions for high-precision material processing. Their ability to provide localized, high-frequency energy is harnessed for applications such as sintering, melting, and surface treatment of advanced materials, including composites and high-performance alloys. This level of control enables the fabrication of complex geometries with superior mechanical and thermal properties, driving advancements in aerospace, biomedical implants, and industrial components [1-6].

These emerging applications underscore the importance of optimizing gyrotron performance, particularly in terms of mode selection and operational stability. The present work addresses these challenges by providing insights into start-up conditions and mode competition management, which are pivotal for the efficient deployment of gyrotrons in these advanced technological domains.

Unlike other microwave tube technologies that rely on velocity modulation, the gyrotron uses a fast-wave interaction mechanism to generate coherent EM radiation. Specifically, it converts the kinetic energy of a gyrating electron beam into electromagnetic energy through cyclotron resonance, resulting in the amplification of transverse electric (TE) modes in an open-ended cavity [7].

The fundamental operating principle of the gyrotron involves a magnetron injection gun (MIG) that produces an annular electron beam with a specific gyrating motion (Fig. 1). This beam is then directed into a vacuum tube, where it interacts with an externally applied static magnetic field. The magnetic field plays a dual role: it compresses the electron beam, thereby enhancing the perpendicular velocity component of the electrons, and it also maintains the beam's confinement, allowing precise control over the beam path as it propagates through the gyrotron. This arrangement creates a current distribution around the tube's central axis, which serves as the source for exciting the cavity's TE mode.

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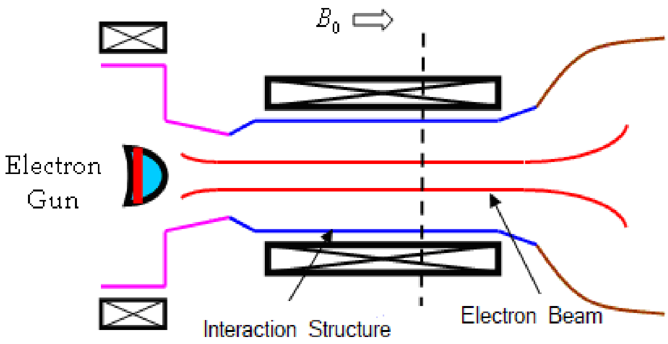

Fig. 1. Cross-sectional view of Gyromonotron

As the electron beam enters the cavity, its perpendicular velocity component couples with the cavity's resonant TE mode, transferring energy to the EM wave through cyclotron resonance. This energy transfer occurs as the electrons spiral around the magnetic field lines, which induces a coherent oscillation in the TE mode due to the periodic alignment of electron gyrations with the cavity’s resonant field. Because the gyrotron cavity is significantly larger than the wavelength of the oscillating EM field, the device operates in an over-moded structure, supporting numerous modes with large azimuthal indices. The annular electron beam, having a radius on the order of the cavity radius, acts as a robust current source with a circular distribution that matches the spatial configuration of the TE mode.

This mode interaction mechanism, unique to gyrotrons, enables efficient power transfer and high-frequency operation while providing the flexibility to operate in various TE modes. However, this over-moded characteristic also presents challenges, as multiple modes can potentially resonate in the cavity, leading to mode competition and reducing efficiency. Therefore, careful design and control of the magnetic field and operating parameters are necessary to suppress undesired modes and ensure stable operation in the target TE mode. Recent advancements in gyrotron technology have addressed these challenges, enabling gyrotrons to achieve reliable high-power output for demanding applications across scientific research, industrial processing, and defense sectors. This paper further explores the specifics of mode control and competition in gyrotron operation, providing insights into optimizing performance for high-frequency, high-power applications.

II. Start-up Conditions

In a gyrotron, achieving steady-state operation requires managing a time-dependent transition phase where the device's parameters gradually settle to the desired operating conditions. During this start-up phase, the gyrotron first meets the self-excitation conditions necessary to initiate oscillations before reaching its nominal operating point. This start-up process is critical to stimulate the target mode at optimal efficiency and power output, while effectively suppressing any competing modes that may interfere with performance [8]-[9].

The self-excitation condition in electron-beam-driven microwave sources, such as the gyrotron, is generally governed by the start oscillation current, I_{start} . This threshold current is the minimum electron beam current required to initiate oscillations in the device, and it is influenced by various parameters including the beam voltage, beam alignment, and the magnetic field strength [10]. When the beam current, I_b, surpasses the start oscillation current, I_{start}, the self-excitation criteria are satisfied, and oscillations begin to grow. With carefully optimized parameters, these oscillations can quickly stabilize, transitioning to a steady-state regime over a brief transient period. The region where I_b is just above I_{start} is often referred to as the "soft self-excitation region." In this regime, oscillations may begin to develop from noise levels generated by the electron beam, leading to a gradual build-up of signal strength.

However, many gyrotron oscillators also possess a "hard self-excitation region," where oscillations do not automatically begin from low noise levels but require a specific minimum initial amplitude to sustain oscillation. In this case, oscillations can only be maintained if they start with an amplitude that exceeds a critical threshold. This hard self-excitation region introduces hysteresis to the system: the presence or absence of oscillations for a given set of parameters depends on the history of those parameters. For instance, if oscillations were initiated under conditions that allowed them to grow, they might continue even as conditions are altered slightly below the original threshold. This hysteresis effect enables the gyrotron to sustain oscillations at high efficiencies, which are generally only achievable in the hard self-excitation regime [10]. To reach this optimal efficiency, it is often necessary to transition through the soft self-excitation region before reaching the most effective operating point within the hard self-excitation region, ensuring that oscillations remain stable throughout this progression.

When a gyrotron is designed to operate in a high-order mode, the start-up process becomes more complex. Higher-order modes present a condensed mode spectrum, meaning that the conditions for self-excitation can be simultaneously satisfied for multiple modes, leading to a higher risk of mode competition. This situation creates a challenge because multiple modes can initiate oscillations simultaneously, potentially interfering with each other and reducing overall efficiency. The ideal start-up procedure, therefore, aims to selectively stimulate the desired operating mode ahead of all others, establishing conditions that allow it to suppress competing modes as the device transitions into steady-state operation.

Mode competition is managed by nonlinear interactions among the modes. When the desired operating mode is present, the threshold current required to initiate a parasitic mode is effectively increased, thereby suppressing these unwanted modes. This phenomenon is known as nonlinear mode competition, and it plays a crucial role in maintaining stable, high-efficiency operation. By selectively increasing the start oscillation current of competing modes through the influence of the primary mode, the gyrotron can maintain oscillation in the desired mode and prevent the growth of parasitic oscillations.

In sum, the start-up conditions of a gyrotron are carefully tailored to pass through a soft self-excitation zone before reaching the hard self-excitation regime, where optimal efficiency is typically achieved. In high-order mode operations, where mode competition is prevalent, nonlinear interactions are harnessed to suppress undesired modes, ensuring stability and efficiency in the desired operating mode.

III. Analysis of Start Oscillation Current

The start-oscillation current, denoted I_{start}, is the minimum electron beam current required to initiate oscillations in a gyromonotron (gyrotron). This threshold is critical, as oscillations only develop when the output power rate of change becomes positive as the current approaches the threshold limit I_{start} [9]-[10]. It is the smallest current for which the rate of change of output power in the limit $P \to 0$ is larger than zero $\left(dP_{out}/dt > 0\right)$. Mathematically, this criterion ensures that the oscillation conditions are met for the desired mode and can be formulated as [9], [11]-[18]:

$$I_{start} = \left(U \left. \frac{d\eta}{dP} \right|_{P=0} \right)^{-1} \quad (1)$$

Stable operation is promising only for $I_b > I_{start}$ and $dP_{out}/dI_b > 0$ where I_b is the beam current, U is the accelerating voltage, η is the efficiency of gyromonotron, and $P = ju_t \exp[-j(\Lambda + \theta)]$, Λ is slowly varying gyro phase, u_t is perpendicular component of dimensionless variable, $u = \gamma v/c$, c is velocity of light, γ is a relativistic factor and is given by $\gamma = \sqrt{1 + u_z^2 + |P|^2}$.

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If the current is below the threshold value, I_{start}, the gyromonotron will not oscillate, which is determined by beam characteristics, magnetic field, resonator shape, and other factors. It can be ensured that the intended mode is aroused with optimal efficiency at the target power level while suppressing surrounding modes by computing and relating the beginning currents of preferred and competing modes.

For a Gaussian field profile $\hat{f}(z) = \exp\left[-\left(2z/L - 1\right)^2\right]$, the start oscillation current is expressed as

$$I_{start}(\Delta, \mu) = 8.56 \times 10^4 \frac{\exp\left[\frac{1}{8}(\mu\Delta)^2\right]}{\mu^2\left(\mu^2\Delta - 4s\right)} \left(\frac{\gamma_0}{Q}\right) \beta_{\perp 0}^{2(3-s)} \left(\frac{L}{\lambda}\right) C_{mp}^{-2} \quad (2)$$

where

$$\mu = \left(\frac{\pi L}{\lambda}\right)\left[\frac{\beta_{\perp 0}^2}{\beta_{z0}}\right] \quad (3)$$

frequency mismatch or detuning parameter,

$$\Delta = \left(\frac{2}{\beta_{\perp 0}^2}\right)\left[1 - \frac{s\Omega_0}{\omega\gamma_0}\right] = \left(\frac{2}{\beta_{\perp 0}^2}\right)\left[1 - \frac{s\omega_C}{\omega}\right] \quad (4)$$

and coupling coefficient,

$$C_{mp}^2 = \frac{J_{m\pm n}^2(k_{mp} r_g)}{(v_{mp}^2 - m^2) J_m^2(v_{mp})} \quad (5)$$

v_{mp} is the p^{th} Bessel zero for TE_{mp} modes defined by $J'_{mp}(v_{mp}) = 0$, and $\omega_C = eB_0/m_e\gamma = \Omega_0/\gamma$, B_0 being axial static magnetic flux density [14-18].

The detuning parameter determines the frequency alignment between the electron beam and the cavity mode, directly affecting the energy transfer efficiency. Similarly, the coupling coefficient quantifies the strength of interaction between the electron beam and the electromagnetic field, playing a critical role in determining which modes are preferentially excited under given operating conditions.

Equation (2) defines the start oscillation current for a Gaussian field profile, linking the threshold current to critical parameters such as frequency mismatch, coupling coefficient, and magnetic flux density. This equation plays a central role in ensuring efficient and stable operation by allowing precise calculation of the conditions necessary for the excitation of the desired mode while suppressing competing modes. Specifically, by optimizing the start oscillation current using Equation (2), the gyrotron can selectively stimulate the desired mode while preventing the growth of parasitic modes, thereby enhancing overall efficiency and mode purity.

Thus, by carefully calculating and optimizing I_{start} for the desired mode, it is possible to ensure that oscillations begin only for the preferred mode. This approach, involving Gaussian field profile parameters, Bessel function characteristics, and a tailored magnetic field, allows the gyromonotron to reach its target power level efficiently while suppressing competing modes. In conclusion, understanding and managing the start-oscillation current are essential for effective gyrotron operation, offering insights into achieving stability, power output control, and mode selectivity.

IV. Analysis of Start Oscillation

A. Simulation Setup and Analysis of 140 GHz Gyrotron Operating Parameters

In this study, MATLAB was utilized to carry out detailed numerical simulations to analyze the start-up conditions and mode competition in a 140 GHz gyrotron. MATLAB's computational tools provide an effective platform for evaluating the interaction between electron beam parameters and the resonant cavity modes, enabling precise control over the device’s operation. The focus of this analysis was a gyrotron configured to operate in the $TE_{10,4}$ mode, a high-order transverse electric (TE) mode, with specific operating parameters. These parameters include the harmonic mode number $\boldsymbol{s = 1}$, beam voltage $\boldsymbol{V_b = 75\,\mathrm{kV}}$, beam current $\boldsymbol{I_b = 6\mathrm{A}}$, velocity ratio $\boldsymbol{\alpha = 1.4}$, and diffraction quality factor $\boldsymbol{Q_d = 1040}$. These values reflect typical design parameters for high-power, high-frequency gyrotrons used in scientific and industrial applications.

The primary goal of this simulation was to optimize the electron beam's position within the cavity to ensure robust excitation of the desired $TE_{10,4}$ mode while effectively suppressing unwanted competing modes, such as $TE_{10,3}$, $TE_{11,4}$, and $TE_{9,4}$. In such high-order mode operations, mode competition is a significant challenge because of the dense mode spectrum, which increases the likelihood of undesired modes being excited alongside the target mode. Therefore, a precise selection of parameters, particularly the beam position and magnetic flux density, is essential to maintain stable and efficient oscillations in the desired $TE_{10,4}$ mode.

The MATLAB simulations included two key analyses: the coupling coefficient versus normalized beam radius (Fig. 2) and the start-oscillation current versus axial magnetic flux density (Fig. 3). These analyses provided critical insights into the optimal configuration for mode selection and mode suppression in the 140 GHz gyrotron.

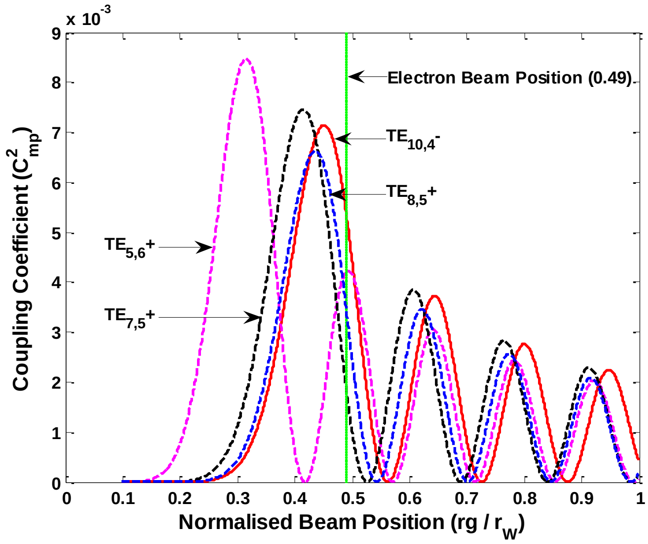

Fig. 2: Coupling coefficient plot identifying the optimal beam location for a 140 GHz gyrotron to maximize TE10,4 mode excitation and suppress competing modes

B. Coupling Coefficient vs. Normalized Beam Radius Analysis

The first analysis focused on plotting the coupling coefficient as a function of the normalized beam radius for the $TE_{10,4}$ operating mode and its main competing modes, $TE_{10,3}$, $TE_{11,4}$, and $TE_{9,4}$. The coupling coefficient, which quantifies the strength of interaction between the electron beam and the cavity's electromagnetic field, is a key factor in determining the efficiency and stability of the gyrotron. This coefficient is influenced by the electron beam's position within the cavity, and an optimal beam position is essential to maximize coupling with the desired mode while minimizing coupling with undesired modes.

MATLAB was used to solve the coupling coefficient equation, which is derived from the field interaction dynamics and resonant mode characteristics, across a range of normalized beam radii. The results are shown in Fig. 2, where the continuous plot represents the coupling coefficient for the desired $TE_{10,4}$ mode, and the dotted plots correspond to the competing modes $TE_{10,3}$, $TE_{11,4}$, and $TE_{9,4}$. By observing the peaks in the coupling coefficient plot for the desired mode, the optimal electron beam radius was identified as the position that maximizes coupling with $TE_{10,4}$ while minimizing coupling with the competing modes. The optimal beam location is crucial, as it ensures that the desired $TE_{10,4}$ mode achieves dominance, reducing the risk of mode competition. At this specific beam radius, the coupling coefficients for competing modes remain below the threshold required for their excitation, thereby suppressing their growth. This selective enhancement of the $TE_{10,4}$ mode is achieved through careful alignment of the electron beam with the cavity's resonant field structure. The electron beam radius chosen based on Fig. 2 is used in subsequent simulations to calculate the start-oscillation current for the operating and competing modes across various magnetic flux densities.

C. Start-Oscillation Current vs. Axial Magnetic Flux Density Analysis

The second analysis involved plotting the start-oscillation current as a function of the axial magnetic flux density B_0 for the $TE_{10,4}$ mode and its competing modes. The start-oscillation current, I_{start} , is the minimum current required to initiate oscillations in a given mode. The magnetic flux density directly influences the start-oscillation current, and selecting the appropriate B_0 value is critical to achieving efficient oscillations in the desired mode.

The start-oscillation current for the $TE_{10,4}$ mode was computed using MATLAB by solving the expression for I_{start} derived from the interaction dynamics, which considers the Gaussian field profile, frequency mismatch (detuning), and coupling coefficient.

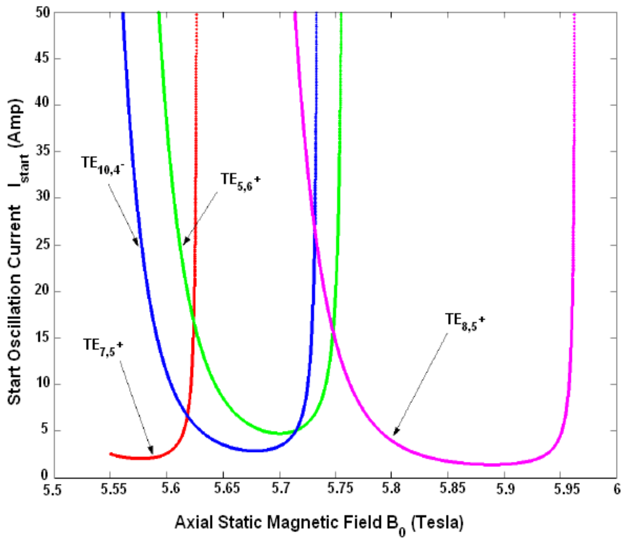

Fig. 3: Start-oscillation current as a function of axial magnetic flux density for a 140 GHz gyrotron, highlighting the magnetic field range that optimizes TE10,4 mode excitation while suppressing competing modes

The plot in Fig. 3 shows the start-oscillation current as a function of the magnetic flux density B_0 for the operating mode $TE_{10,4}$ and the competing modes. By analyzing this plot, it is possible to identify the magnetic flux density ranges where the start-oscillation current is minimized for the desired mode, ensuring efficient excitation of $TE_{10,4}$ while avoiding competing modes.

From the plot (Fig. 3), it was observed that for B_0 values between 5.3 and 5.5 Tesla, the start-oscillation current for the competing mode $TE_{10,3}$ was minimized. Similarly, for values in the range of 5.0 to 5.3 Tesla and 5.5 to 5.7 Tesla, the start-oscillation current for $TE_{11,4}$ and $TE_{9,4}$ was minimized, respectively. These magnetic flux density ranges are undesirable for stable operation in the $TE_{10,4}$ mode, as they promote oscillations in competing modes.

To ensure that only the $TE_{10,4}$ mode is excited, a magnetic flux density of B_0=5.68 Tesla was selected. At this point, the start-oscillation current for $TE_{10,4}$ is minimized while the start-oscillation currents for the competing modes remain above the excitation threshold, effectively suppressing them. The choice of B_0=5.68 Tesla thus allows for the selective excitation of the $TE_{10,4}$ mode, achieving the desired oscillation efficiency and mode purity without interference from surrounding modes.

V. Conclusion

This analysis demonstrates that careful selection of both the electron beam position and the magnetic flux density is essential for optimizing the start-up conditions of a 140 GHz gyrotron operating in the $TE_{10,4}$ mode. By analyzing the coupling coefficient as a function of beam radius, the optimal electron beam location was identified, enabling maximum coupling with the desired mode and minimal coupling with competing modes. Further, by examining the start-oscillation current across different magnetic flux densities, a specific B_0 value of 5.68 Tesla was chosen, ensuring efficient excitation of the $TE_{10,4}$ mode while suppressing unwanted modes. This approach enables stable, high-efficiency gyrotron operation at the target frequency and power level, contributing to advancements in high-frequency, high-power applications such as plasma diagnostics, material processing, and RF sources for particle accelerators.

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