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SELF-CONSISTENT EFFECTS ON THE STARTING CURRENT OF GYROTRON OSCILLATORS

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Abstract

Self-consistent effects on the starting current of gyrotron oscillators are examined. Field profiles in the open cavity are shown to be sensitive to the interaction dynamics. This can either significantly raise or lower the oscillation threshold, particularly for the low-Q modes. The transition from resonant-mode oscillations at the low magnetic field to backward-wave oscillations at the high magnetic field is demonstrated.

Keywords: gyrotron oscillator, open cavity, self-consistent field profile, start-oscillation current.

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I. Introduction

The gyrotron oscillator is a coherent radiation source based on the electron cyclotron maser interaction [1]. High average power up to the MW level and high operating frequency up to hundreds of GHz have been demonstrated [2-6]. These powerful sources are being used in a variety of scientific researches and industrial applications, such as fusion plasma heating [7, 8], material characterization and processing [9], plasma wave scattering [10], and electron spin resonances [11].

Figure 1a shows a typical open cavity employed in the gyrotron oscillator. In operation, a helical electron beam is injected into the cavity in the presence of a static magnetic field. Sophisticated codes (see, for example, [12]-[15]) have been developed for self-consistent modeling of the interaction process. On the other hand, analytical linear theories in a fixed field profile (see, for example, [16]-[18]) provide convenient tools for first-cut design studies and, in particular, the evaluation of start-oscillation currents. In the present study, we employ a self-consistent code [15] to examine the linear properties of the oscillator in a broad range of magnetic field.

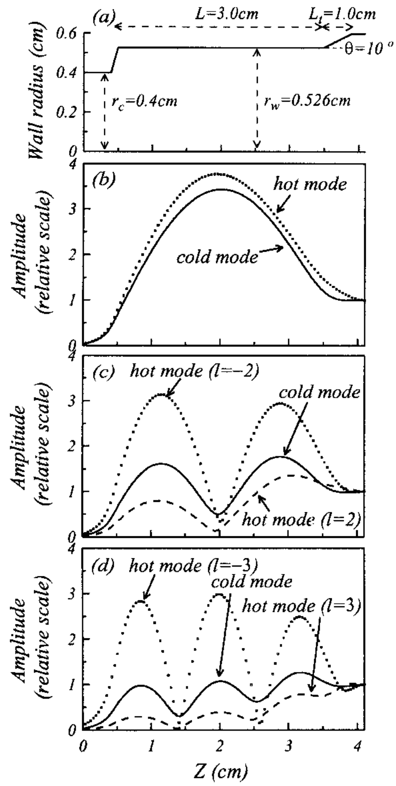

Fig.1 (a) Configuration and dimensions of the interaction structure under study. (b) - (d) Field profiles of the first three axial modes (ℓ =1, 2, and 3). Hot modes are self-consistently calculated and shown in broken lines. Cold modes are shown in solid lines.

II. Model and Assumptions

We consider the fundamental cyclotron harmonic interaction between the electron beam and the TE_{01} mode of the cavity shown in

Fig. 1a. The magnetic field is assumed to be uniform. The beam voltage and electron velocity ratio are fixed at $V_b = 70\,\text{kV}$ and $v_\perp / v_z$ = 1.5 respectively, with the electron guiding centers located at the radial peak of the rf electric field. A cold beam is assumed and space charge effects are neglected.

Dimensions of the cavity are indicated in Fig. 1a. In the absence of beam loading, calculated resonant frequencies of the $TE_{01\ell}$ modes are 35.03, 35.83, and 37.14 GHz for ℓ =1, 2, and 3, respectively, where ℓ is the axial mode index. The corresponding quality factors are 317, 85, and 41. Axial modes of still higher orders virtually overlap into a continuum because of their rapidly decreasing Q values.

III. Self-Consistent Field Profiles

Gyromonotrons are normally designed to operate in the fundamental axial mode. Dimensions of the cavity under study have been chosen for a high theoretical interaction efficiency of 42% for this mode. Here, to accentuate the self-consistent effects as well as to show the transition into the continuum regime, we shall look more closely into interactions involving higher order axial modes.

The ℓ-th axial mode is formed of two traveling-wave components with propagation constants,

$$k_z = \pm \ell \pi / L_{eff}, \tag{1}$$

where L_{eff} is the effective length of the cavity. The electrons can resonantly interact with either component, provided the electron transit angle Θ with respect to that component falls in the range

$$0 < \Theta < \pi, \tag{2}$$

where Θ is defined as

$$\Theta = (\omega - k_z v_z - \Omega_c)\tau, \tag{3}$$

and Ω_c , v_z , and τ are, respectively, the electron cyclotron frequency, axial velocity, and transit time. Thus, cyclotron resonance with each traveling-wave component occurs in a different region of the magnetic field.

For convenience, we denote the forward (backward) traveling-wave interaction by a positive (negative) axial mode index. For the fundamental axial mode, resonant regions of the $\ell = \pm 1$ components partially overlap so that the interaction involves both components. Figure 1b displays the start-oscillation field profile (dotted line) of the fundamental axial mode evaluated at the magnetic field optimized for minimum start-oscillation current. The cold cavity profile is also plotted for comparison (solid line). Field profiles are normalized to the same output power, so that their relative amplitudes can be meaningfully interpreted. Because the fundamental mode has a relatively high Q value, the hot and cold field profiles are only slightly different. For beam interactions with a higher order axial mode ($\ell \geq 2$), however, there are two isolated regions of resonant magnetic field for the $\pm\ \ell$ components. As a result, there will be two hot field profiles for each axial mode, one in each region of the resonant magnetic field. Figure 1c shows the start-oscillation field profiles (dashed and dotted lines) for the second axial mode generated at their respective optimum magnetic field. The profiles are again normalized to the same output power and the cold field profile is shown for comparison (solid line). It is seen that hot field profiles are significantly different from the cold field profile. Furthermore, the hot field profiles are even more different from each other. The field generated through the forward-wave interaction peaks toward the downstream end, whereas the backward-wave interaction generates a field peaking at the opposite end. Similar but greater differences are shown in Fig. 1d for the third axial mode.

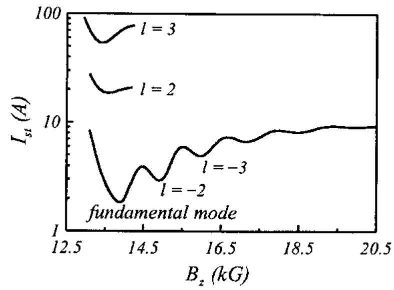

Fig.2 Starting current (I_{st}) versus magnetic field (B_z) for TE_{01}-mode interactions

IV. Start-Oscillation Current

Implications of self-consistent field profiles on the start-oscillation current are shown in Fig. 2. When the field peaks upstream, the electron beam is strongly energy-modulated as soon as it enters into the cavity and becomes tightly phase bunched as it propagates downstream. By comparison, the field with a downstream peak is much less favorable for electron bunching. In addition, for the field with an upstream peak, there is a higher ratio of field energy to output power, thus a higher Q value. These two factors result in almost one order of magnitude difference in the start-oscillation currents for the two profiles, as shown in Fig.2.

Broader resonant width of higher order axial modes results in greater mode overlapping. Hence, it is seen in Fig. 2 that the discrete modal structure at the low magnetic field transition to a continuum at a higher magnetic field.

V. Conclusion

High order axial modes of the open cavity are shown to be strongly influenced by the interaction dynamics. Depending on the magnetic field at which it is excited, a high order axial mode can assume two distinctively different profiles with drastically different threshold currents. It is also shown that, through the magnetic field tuning, a resonator-based gyrotron oscillator can be made to perform dual functions, as a gyromonotron or a reflective-type gyro-BWO.

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V. References

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