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# Coupled-mode theory of coaxial gyrotron with two electron beams

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**Abstract**

Results of coupled-mode theory for the study on coaxial gyrotron with two electron beams (CGTB) are given. The beam–wave interactions of single-mode and dual-mode CGTB are discussed in details. Compared with the coaxial gyrotron with one beam (CGOB), the dual-mode CGTB has distinguished advantages: the fundamental and high harmonic can be enhanced due to the coupling between two beams.
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*Keywords:* Coaxial gyrotron; Two electron beams; Dual-mode; Coupled-mode theory

## 1. Introduction

The research on gyrotrons remains to be one of the most attractive topics in modern science and technology for the following important motivations: the strong demand of very high RF power for fusing research, the ITER program requires up to 1–2 MW, CW at 170 GHz [1–4] the high power is also needed for various applications including those in Terahertz science and technology [5,6]. In order to increase the output power, very high order modes in coaxial cavity gyrotron, $TE_{34,19}$, etc., for instance, are used [3]. However, up to now the real CW 1–2 MW gyrotron is not yet achieved [3,4]. In addition, the mode competition is serious in these gyrotrons due to very high order mode operation. The gyrotron with two electron beams in a coaxial cavity has proposed [7–9]. The device has a number of advantages, the output power can be enhanced and the mode competition can be significantly improved. In this article, we will use the coupled-mode theory to investigate the beam-wave interactions of the coaxial gyrotron with two electron beams (CGTB) operating at single-mode and at two modes with different cyclotron harmonics and compare the beam-wave interactions of dual-mode CGTB with those of CGOB (coaxial gyrotron with one beam).

## 2. The theory of approach

### 2.1. Single-mode CGTB

The cross-section of a CGTB is showed in Fig. 1a and b denotes the outer and inner radii of the coaxial waveguide system. The radii of the guiding center of beam 1 and beam 2 are $R_1$ and $R_2$, respectively.

For TE modes in a perfectly conducting coaxial waveguide, the **E** and **H** components of the electromagnetic field form the following complete and orthogonal set of eigenfunctions [10]

$$\begin{cases} \vec{E}(\vec{r},t) = \displaystyle\sum_{n=-\infty}^{+\infty} v_n(z,t)\vec{E}_{tn}(\vec{r_\perp}) \\ \vec{H}(\vec{r},t) = \displaystyle\sum_{n=-\infty}^{+\infty} i_n(z,t)\vec{H}_{tn}(\vec{r_\perp}) + p_n(z,t)\vec{H}_{zn}(\vec{r_\perp}) \end{cases} \quad (1)$$

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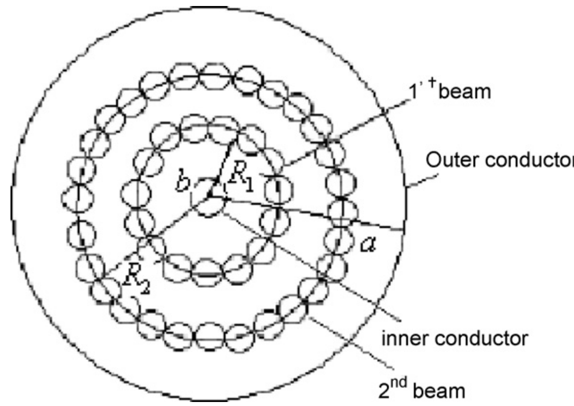


Fig. 1. Schematic cross-section of the CGTB.

Here $\vec{r}$ is the position vector, $z$ the axis of the waveguide, $\vec{r}_\perp$ the position vector in the plane perpendicular to the $z$ axis and $t$ is the time. Substituting Eq. (1) into the inhomogeneous Maxwell equations

$$\begin{cases} \nabla \times \vec{E} = -\mathrm{j}\omega\mu_0 \vec{H} \\ \nabla \times \vec{H} = \mathrm{j}\omega\varepsilon_0 \vec{E} + \vec{J}_\mathrm{b} \end{cases} \tag{2}$$

we can obtain the following expressions

$$\sum_n \left( \frac{\partial v_n}{\partial z} \vec{H}_{tn} - j v_n \omega\mu_0 \vec{H}_{zn} \right) = -\mathrm{j}\omega\mu_0 \sum_n (i_n \vec{H}_{tn} + p_n \vec{H}_{zn}) \tag{3}$$

$$\sum_n \left( \frac{\partial i_n}{\partial z} \vec{E}_{tn} - i v_n \frac{k_{cn}^2}{\omega^2 \mu_0} \vec{E}_{tn} \right) = -\mathrm{j}\omega\varepsilon_0 \sum_n v_n \vec{E}_{tn} - \vec{J}_\mathrm{b} \tag{4}$$

where $\vec{J}_\mathrm{b}$ is the beam current density. For the CGTB, $\vec{J}_\mathrm{b} = \vec{J}_1 + \vec{J}_2$, $\vec{J}_1$, $\vec{J}_2$are the current density of beam 1 and beam 2, respectively. Multiplying both sides of Eq. (3) by $\vec{H}_{tn}^*$, Eq. (4) by $\vec{E}_{tn}^*$, and integrating over the cross-section of the waveguide, we can obtain the following equations

$$\frac{\partial a_{1\pm}}{\partial z} = \mp jk_{z1} a_{1+} \mp \frac{1}{2}\sqrt{\frac{Z_1}{2}} A \tag{5}$$

Here we have introduced the following new variables

$$a_{1\pm} = \frac{1}{2\sqrt{2Z_1}}(-v_1 \pm Z_1 i_1) \tag{6}$$

and

$$A = \int_s (\vec{J}_1 + \vec{J}_2) \cdot \vec{E}_{t1}^* \, \mathrm{d}s \tag{7}$$

where $Z_1 = \omega\mu_0/k_{z1}$, $k_{z1}^2 = k^2 - k_{c1}^2$, $k_{c1}$ is the cutoff wave number of the mode, $k=\omega/c$, where $\omega$ is the angular frequency of electromagnetic wave, $c$ is the light velocity in vacuum.

In order to get the perturbed equation of electron motion in the electron-guiding center coordinate system, we assume [11]

$$\begin{cases} \gamma = \gamma_0 + \gamma_1\,; \quad |\gamma_1| << |\gamma_0|\,; r = r_0 + r_1\,; \quad |r_1| << |r_0| \\ \theta = \theta_0 + \theta_1\,; \quad |\theta_1| << |\theta_0|\,; z = z_0 + z_1\,; \quad |z_1| << |z_0| \end{cases} \tag{8}$$

According to the relativistic equation of electron motion, introducing the following new variables

$$\begin{cases} v_+ = \dot{r}_1 + jr_0\dot{\theta}_1 \\ v_- = \dot{r}_1 - jr_0\dot{\theta}_1 \end{cases} \tag{9}$$

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