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

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Abstract—**Coupled-mode theory for the study on the terahertz coaxial gyrotron with two electron beams (CGTB) is discussed in details. The beam-wave interactions of dual-mode terahertz CGTB are investigated, compared with the terahertz coaxial gyrotron with one beam (CGOB), the dual-frequency CGTB has distinguished advantages: the fundamental and high harmonic can be enhanced due to the coupling between electrons beam and modes.**

I. Introduction And Background

Because of the strong demand of very high RF power for fusing research, the ITER program requires up to 1-2 MW,CW at 170GHz[1] and various applications including those in Terahertz science and technology[2], the research on gyrotrons remains to be one of the most attractive topics in modern science and technology. In order to increase the output power and improve the mode competition, the gyrotron with two electron beams in a coaxial cavity has been proposed [3]. The device has a number of advantages, the output power can be enhanced and the mode competition can be significantly improved. In this paper, we will use the coupled-mode theory to investigate the beam-wave interactions of the CGTB operating at two modes with different cyclotron harmonics and compare the beam-wave interactions of dual-mode CGTB with those of CGOB.

II. THE THEORY OF APPROACH

The cross section of a CGTB is showed in Fig.1, a, b denote 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.

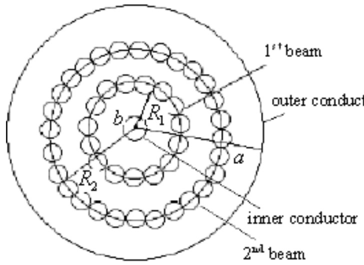

Fig.1 Schematic cross section of the CGTB

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[4]

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

Substituting eq. (1) into the inhomogeneous Maxwell equations

$$\begin{cases}\nabla\times\vec{E}=-j\omega\mu_0\vec{H}\\ \nabla\times\vec{H}=j\omega\varepsilon_0\vec{E}+\vec{J}_b\end{cases}\qquad(2)$$

where $\vec{J}_b$ is the beam current density. For the CGTB, $\vec{J}_b=\vec{J}_1+\vec{J}_2$, $\vec{J}_1$, $\vec{J}_2$ are the current density of beam 1 and beam 2, respectively. According to the relativistic equation of electron motion[5] and eqs.(1) and (2), for the dual-mode CGTB we can obtain the dispersion relationship

$$\begin{aligned}&[(\Omega_1+\Omega_2-\dot{\theta}_0)(k^2-k_{z1}^2)+j\frac{(C_{10}^1C_{11+}+C_{20}^1C_{21+})k_{z1}\sqrt{Z_1}}{\sqrt{2}}]\\ &\cdot[(\Omega_1+\Omega_2-\dot{\theta}_0)(k^2-k_{z2}^2)+j\frac{(C_{10}^2C_{12+}+C_{20}^2C_{22+})k_{z2}\sqrt{Z_2}}{\sqrt{2}}]\\ &+\frac{1}{2}[C_{10}^2C_{11+}+C_{20}^2C_{21+}][C_{20}^1C_{22+}+C_{10}^1C_{12+}]k_{z1}\sqrt{Z_1}k_{z2}\sqrt{Z_2}=0\end{aligned}$$

(3)

We have introduced the following new variables

$$\begin{cases}c_{10}^i=2\pi R_1r_0\rho_{10}(1-\frac{l_i\dot{\theta}_0}{\Omega_i})(E_{1t\theta}^*+E_{2t\theta}^*)\\ c_{20}^i=2\pi R_2r_0\rho_{10}(1-\frac{l_i\dot{\theta}_0}{\Omega_i})(E_{1t\theta}^*+E_{2t\theta}^*)\end{cases}\qquad(4)$$

$$\begin{aligned}C_{ij\pm}=\sqrt{2Z_j}\{&\frac{f_{ijr}^{'}\pm jf_{ij\theta}^{'}}{m_0\gamma_0}+j\frac{r_0\dot{\theta}_0}{m_0\gamma_0c}(\beta_\perp f_{ij\theta}^{'}+\beta_{//}f_{ijz}^{'})\\ &\cdot(\frac{\dot{\theta}_0}{\Omega_j}\pm1)\}/N_i\quad i=1,2;\,j=1,2\end{aligned}\qquad(5)$$

Where $N_i^2=\int_s\vec{E}_{itn}\cdot\vec{E}_{itn}^*\,ds$, $f_{ij}^{'}=f_{ij}/N_iv_i$, f_{ij} is the force of mode j to beam i.

For the CGOB, using the same method discussed above, we can obtain the dispersion equation of the CGOB operating at mode 1 with beam 1

$$(\Omega_1-\dot{\theta}_0)(k_{//}^2-k_{z1}^2)+\frac{jC_{11+}C_{10}k_{z1}\sqrt{Z_1}}{\sqrt{2}}=0\qquad(6)$$

The dispersion equation of CGOB operating at mode 2 with beam 2

$$(\Omega_2-\dot{\theta}_0)(k_{//}^2-k_{z2}^2)+\frac{jc_{22+}c_{20}k_{z2}\sqrt{Z_2}}{\sqrt{2}}=0\qquad(7)$$

In eqs. (6), (7), we have introduced the following variables

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$$
\begin{cases}
c_{10} = 2\pi e R_1 r_0 \rho_{10} \left(1 - \dfrac{l_1 \dot{\theta}_0}{\Omega_1}\right) E^*_{1t\theta} \\
c_{20} = 2\pi e R_2 r_0 \rho_{20} \left(1 - \dfrac{l_2 \dot{\theta}_0}{\Omega_2}\right) E^*_{2t\theta}
\end{cases} \tag{8}
$$

III.RESULTS

For simple verification of the principle of the dual-mode CGTB, the CGTB concerned operates at the fundamental harmonic 100GHz and the second harmonic 200GHz. The axial symmetric modes TE_{02} and TE_{04} are selected as the operating modes, because the cutoff frequency of TE_{04} is almost twice that of TE_{02} in the coaxial waveguide and the operating frequency of gyrotron is nearly at the cutoff frequency of the coaxial waveguide. The dispersion curves of the dual-mode CGTB, and the CGOB with the same geometrical parameters are showed in Fig.1. curve ① represents the dispersion curve of TE_{02} mode excited by 1st cyclotron harmonics of beam 1 and TE_{04} mode excited by 2nd cyclotron harmonics of beam 2 of the CGOB; curve ② represents the dispersion curve of dual-mode CGTB. k_{c1} in Fig.1 is the cutoff wave number of TE_{02}. From Fig.1 we can conclude that when two modes are considered simultaneously, because of the coupling between two beams and two modes, compared with CGOB, the maximum of growth rate of TE_{02} mode and TE_{04} mode of dual-mode CGTB are enhanced

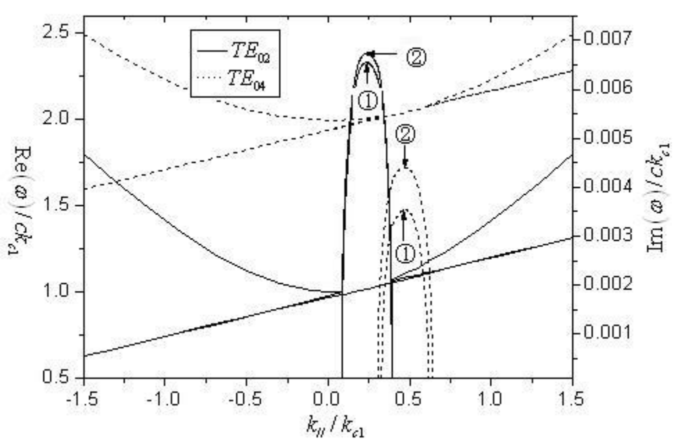

Fig.1 Dispersion curves (a=7 mm, b=4mm, R_1=4.7mm, R_2=5.5mm, mode 1: TE_{02}, mode 2:TE_{04}, U_1=U_2=50keV, I_1=I_2=10A)

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