Invited Paper

Experimental and theoretical investigations on coaxial gyrotron with two electron beams

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Abstract: The coaxial gyrotron with two electron beams is investigated in this paper. The results of the linear and nonlinear theory calculation show that CGTB has some distinguished advantages, such as improved mode competition and enhanced output power, so CGTB may be capable of providing 2-4 *MW* continuous-wave output power at 170 *GHz* to meet the demand of ITER Program. The results of the numerical calculation and PIC simulation show that CGTB can operate at two different frequencies simultaneously. In addition, the power of the high harmonic can be enhanced due to the nonlinear coupling between two electron beams. The prototype of CGTB is fabricated and the verification experiment is being conducted in progress.

Keywords: Terahertz, Coaxial gyrotron with two electron beams, Dual-frequency operation.

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1. Introduction

Two of the main goals for the development of microwave sources in practical applications are to increase the radiated power and to shorten the wavelength. Unlikely so-called “slow-wave” microwave devices, “fast-wave” devices such as gyrotron oscillators and amplifiers rely on a resonance between the modes of an open resonant cavity and the electron beam in a magnetic field. The resonant cavity is usually overmoded, so its physical dimension can be much larger than the operating wavelength. This permits high peak and average power operation even at millimeter and THz region without risking the damage to the interaction cavity [1-4].

Gyrotrons are members of a specific family of devices in the class of vacuum electronic sources of coherent microwave radiation known as electron cyclotron masers (ECMs) or cyclotron resonance masers (CRMs). The operation of electron cyclotron masers is based on the cyclotron maser instability which gives rise to electromagnetic perturbations in the motion of electrons gyrating in an external (quasi-) uniform magnetic field. This instability originates from the relativistic dependence of the electron cyclotron frequency on the electron energy. The gyrotrons are cyclotron resonance masers in which the interaction of helical electron beams with electromagnetic waves takes place in nearly uniform waveguides near their cutoff frequencies [5].

Presently, gyrotrons are the most powerful sources of millimeter, sub-millimeter and terahertz wave radiation capable of continuous-wave operation [6-8]. They are important for numerous applications, which include plasma diagnostics [9], electron-spin resonance spectroscopy [10], enhancement of NMR sensitivity using dynamic nuclear polarization [11-14], standoff detection and imaging of explosives and weapons [15], new medical technology [16], atmospheric monitoring chemical technologies, and production of high-purity materials. The ITER Program requires 1-2 *MW* continuous-wave (*CW*) gyrotrons at 170 *GHz* [17]. In order to increase output power, very high order modes in a coaxial cavity gyrotron are used, for instance $TE_{34,19}$, etc. However, up to now, a real CW 1-2 *MW* gyrotron has not been achieved yet. In addition, mode competition is serious in those gyrotrons due to very high order modes operation.

The coaxial cavity gyrotron with two electron beams (CGTB) is proposed in the papers [1-2]. CGTB has some distinct advantages: the space charge effects are decreased; the mode competition is improved; the loading of the cathode is released. It is of significance for the fusion research, the radar system and other applications as well. Meanwhile, when one electron beam operates at fundamental cyclotron harmonic, the other beam operates at higher cyclotron harmonic; CGTB can operate at two modes with different operating frequencies simultaneously [18].

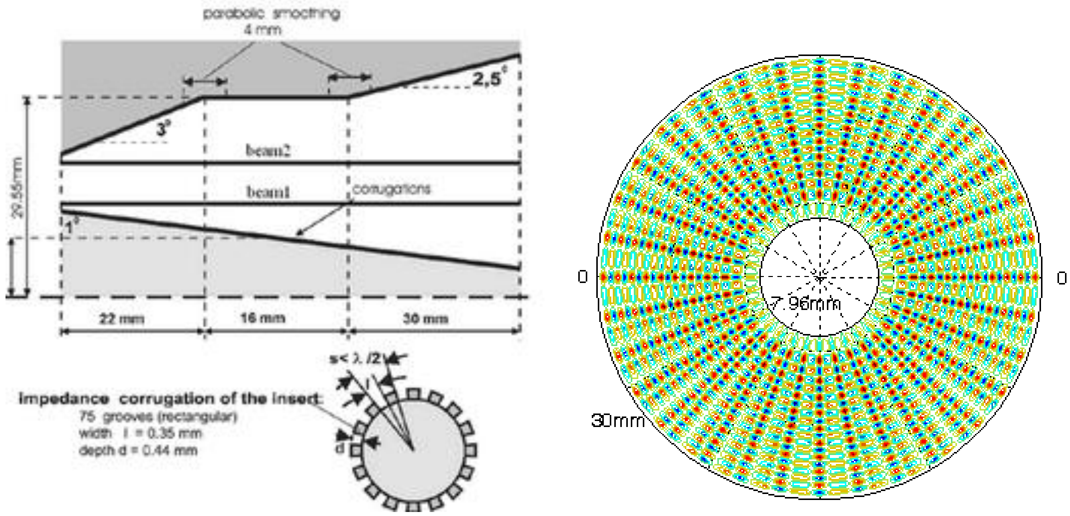
2. Single-frequency operation CGTB

For the single-frequency operation CGTB, in order to make an exact comparison between the investigations presented in this paper and the experimental studies, the operation mode and all parameters of the coaxial gyrotron with one electron beam (CGOB) of the experiments studies in the Forschungszentrum Karlsruhe (FZK) [19]. The geometrical structure and the operation mode of CGTB are shown in Fig. 1. The inner and outer conducting cylinders provide the same electric potential, and it enables the use of two electron beams because it can guarantee the potential of two electron beams to be equal or almost equal to the synchronization of the beam-wave interaction in CGTB.

With the kinetic theory based on the guiding center coordinate system, the starting currents of the two beams electron cyclotron resonance maser (ECRM) in a coaxial resonant cavity are given below [17].

$$I_{st} = -\pi k_c a^2 v_z \gamma (1-\frac{b}{a^2}) H_m \Big/ \eta_0 \mu_0 (1-\frac{q^2\lambda^2}{4L^2}) Qr \left[\sum_{i=1}^{4}\sum_{k=1}^{2} \mathrm{Re}(\frac{P_i}{A_k}) \right] \quad (1)$$

Where L is the length of the beam-wave interaction region, Q_T is the total quality factor of the coaxial resonant cavity. P^i_j is one of components of the beam-wave interaction power. The mode competition of the CGTB can be investigated according to calculations of starting currents I_{st} for operation mode and main parasitic modes.



(a) (b)

Fig. 1 Geometrical structure and operation mode of CGTB. (a) Geometrical structure, (b) the operation mode

The numerical calculation results for mode competition of CGTB and COTB are shown in Fig.2. It is found that for operation mode $TE_{34,19}$, the main parasitic modes are $TE_{-33,19}$, $TE_{-34,19}$, $TE_{-35,19}$, $TE_{33,20}$, $TE_{34,20}$, etc., and it agrees well with the results of the experiments. It can be seen clearly from Fig. 2 that the mode competition of CGTB is greatly improved compared with that of CGOB.

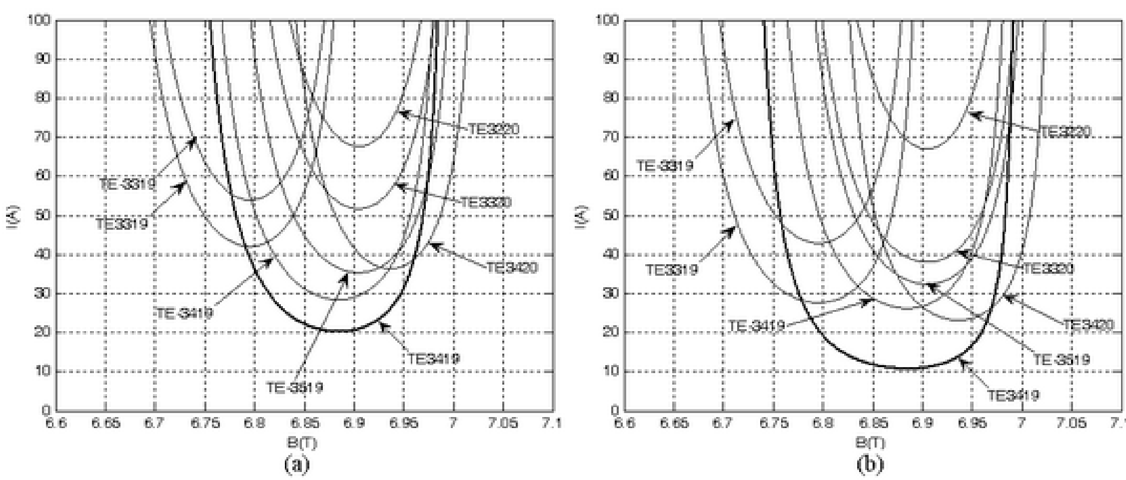


Fig. 2 Mode competition. (a). CGOB; (b). CGTB

According to the relativistic motion equation of electrons, and the Maxwell's equations with a current source, the following transmission line equations with a current source for the azimuthally symmetric system can be obtained.

$$\frac{d^2 f(z)}{dz^2}+\left(\frac{\omega^2}{c^2}-k_c^2(z)\right)f(z)=-j\omega\mu_0\sum_{i=1}^{2}\frac{I_{i0}}{u_{z0}}\int_S \vec{u}_\perp(\vec{r},t)\cdot\vec{E}_{t0}\cdot e^{j\omega t}dS \qquad (2)$$

Where $f(z)$ is the RF electric amplitudes, and I_{i0} is the current of the electron beam i (i=1,2). The results of nonlinear calculation on the efficiency of both CGTB and CGOB are shown in Fig. 3. As mentioned above, for practical comparison, all parameters of CGTB have the same values as those given in the experiment of FZK. It can be seen in Fig. 3 that a similar efficiency can be achieved for CGTB, although the parameters of CGTB were not optimized for two beam operations, and the output power of CGTB may reach 4 *MW*.

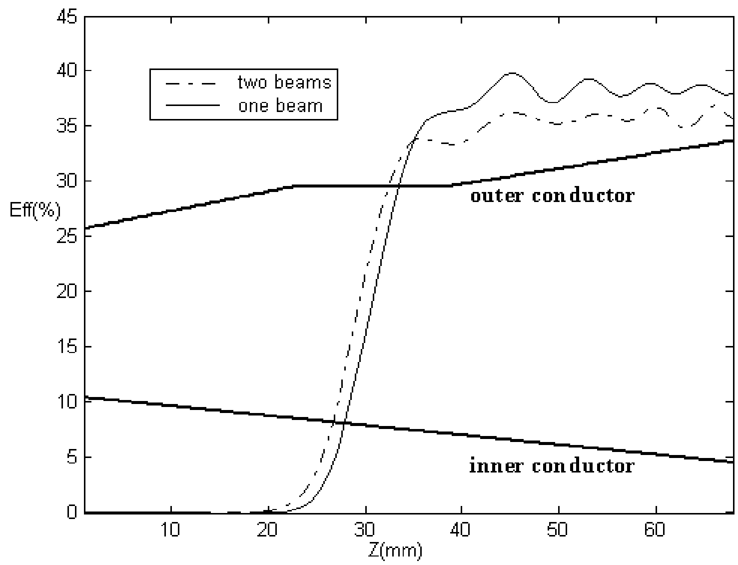
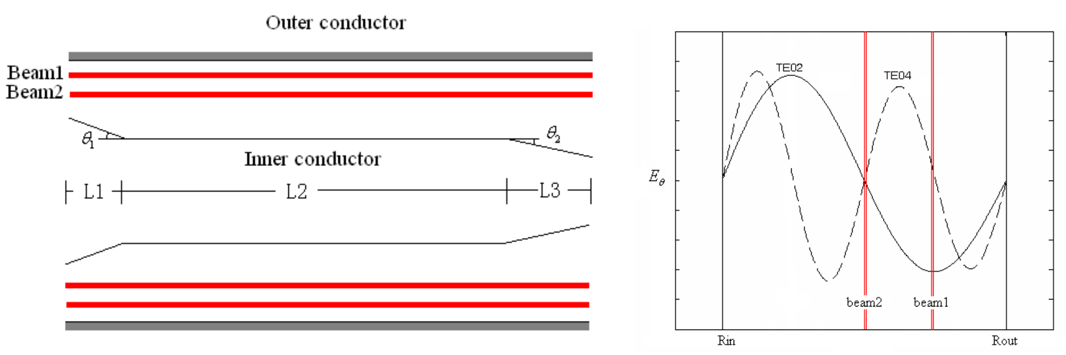


Fig. 3 The efficiency of CGTB for $TE_{34,19}$ mode. The efficiency of CGTB is about 36%, and that of CGOB is about 38%.

3. Dual-frequency operation CGTB

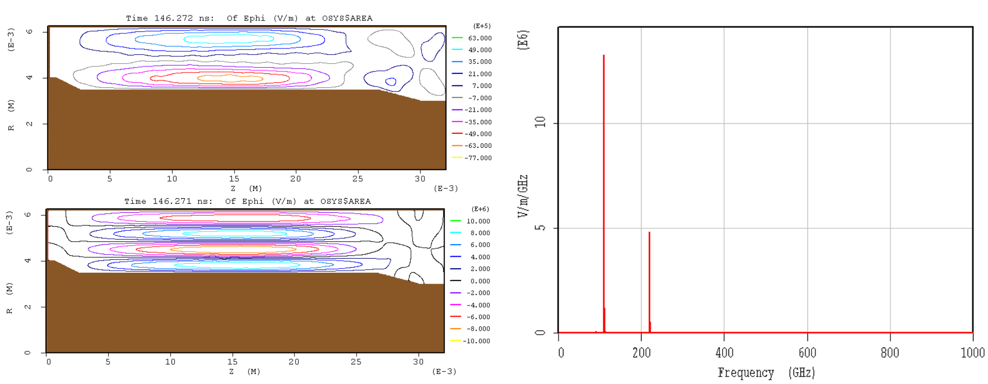
Dual-frequency operation CGTB is a special operation of CGTB: one beam works at the first cyclotron harmonic while the other at the higher cyclotron harmonic. It means that the dual-frequency operation CGTB can provide high power with two different frequencies. It is significant for the fusion research, the radar system, and other applications as well. The geometric structure of the beam-wave interaction cavity and the positions of two electron beams are shown in Fig. 4. The outer and inner radii are 3.5 *mm* and 6.23 *mm*, respectively. The operation modes are TE_{02} and TE_{04} modes, and the corresponding operation frequencies are 0.11 *THz* and 0.22 *THz*.



(a) (b)

Fig. 4 Geometric structure and the position of electron beams of the dual-frequency operation CGTB. (a) geometric structure of the beam-wave interaction cavity; (b) positions of the electron beams.

The field distribution of E_θ and the spectrum of the dual-frequency operation CGTB are presented in Fig.5 with PIC simulation. It is found that the two operation modes can work simultaneously.



(a) (b)

Fig. 5 Field distribution and the spectrum of the dual-frequency operation CGTB. (a) E_θ; (b) the spectrum of the dual-frequency operation CGTB

4. Verification experiment of CGTB

In order to verify the principle of CGTB, the magnetron injection gun (MIG) for two beams has also been designed too. The structure and the trajectories of two beams are shown in Fig. 6. It shows that the inner and outer conductors of the coaxial cavity providing the potential for the corresponding inner and outer electron beams.

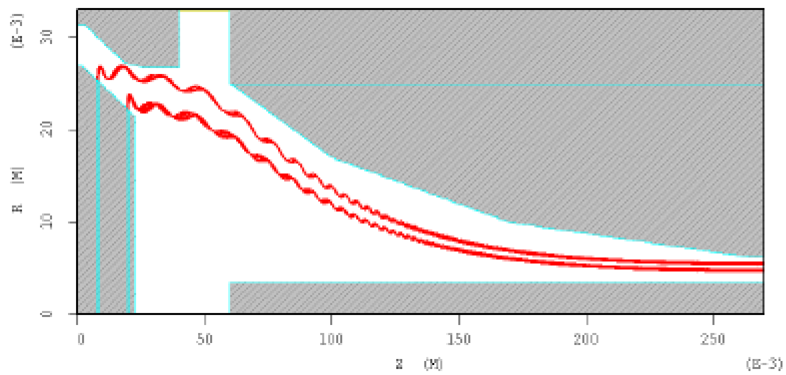
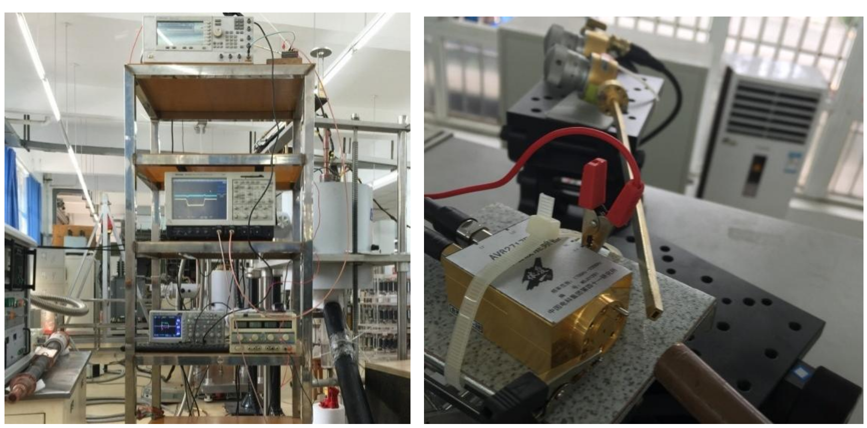


Fig. 6 The structure and the trajectories of two electron beams in magnetron injection gun

The prototype of CGTB is shown in Fig.7. The experimental setup for CGTB is presented in Fig.8. A 220 *GHz* frequency mixer is used to measure the second-cyclotron-harmonic signal, and a 3 *mm* detector is utilized to detect the fundamental-cyclotron-harmonic signal.

Fig. 7 The prototype of CGTB



(a) (b)

Fig. 8 Experimental setup for CGTB.

5. Summaries and Conclusions

Compared with coaxial gyrotron with one electron beam, coaxial gyrotron with two electron beams has distinguished advantages. For instance, mode competition is greatly improved, and output power is enhanced. In particular, CGTB might be capable of providing 2-4 *MW* CW at 170 *GHz* to meet the demand of the ITER program. Meanwhile, CGTB can operate at two different frequencies simultaneously with theoretical predication and PIC simulation. The prototype of CGTB is fabricated and the verification experiment is being conducted in progress.

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