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Numerical study and simulation of a 170 GHz megawatt-level corrugated coaxial-gyrotron

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ABSTRACT

As the sources of high-power microwave and terahertz, gyrotrons have important development prospects. However, there are many difficulties to be resolved in study and design of gyrotrons meeting requirements. In this paper, the beam-wave interactions of a 170 GHz megawatt-level corrugated coaxial-gyrotron are studied numerically. In order to attain high efficiency and stable radiation, $TE_{31,12}$ mode that lies in a relative sparse spectrum is selected as the operating mode and the beam-wave coupling coefficient, and start oscillation current are calculated by a set of source codes. Taking into account electronic velocity spread, and cavity wall resistivity and basing on single-mode approximation, the optimized design and simulation of beam-wave interaction of a 170 GHz MW corrugated coaxial-gyrotron have be fulfilled. The relationships between the efficiency and magnetic field, voltage, current, and parameters of groove are presented. The results show that voltage and magnetic field have great influences on efficiency, but the current and velocity spread do slightly, so reduce the requirements of electronic gun design. In addition, the optimized geometry parameters can improve efficiency, reduce the impact of velocity spread on efficiency, and achieve around 48.6% electronic efficiency and 1.7 MW output power at 5% velocity spread, and 6.896×10^{-8} Ω m resistivity.

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1. Introduction

As the sources of efficient and stable high-frequency and high-power microwave, gyrotrons are widely used in high-resolution radar, communications, electron cyclotron plasma heating, and electron cyclotron current drive etc. Driven by the growing demands, gyrotrons are developing forward higher frequency and higher power. Electron cyclotron plasma heating and current drive in thermonuclear fusion reactors require a gyrotron of frequency of 100–170 GHz, power up to megawatt, width of pulse up to 500 s (or continuous wave), and efficiency of about 50% .Therefore,study and design of gyrotron meeting requirements in thermonuclear fusion reactors are the important task of researchers from all over the world. Institute of Applied Physics (IAP/GYCOM) in Russian, Japan Atomic Energy Research Institute (JAEA), Communications and Power Industries in American, and other institutes have carried out research in conventional cylindrical-cavity gyrotrons. They have made considerable progress and achieved quasi-continuous-wave (the width of pulse in 60 s and above) output, about 50% efficiency, and megawatt power [1–5]. At the same time, coaxial gyrotrons have been proposed. Differing from conventional gyrotrons, there is a longitudinal corrugated tapered insert in coaxial cavity. Due to the structural changes, coaxial gyrotrons have some different characteristics differing from conventional gyrotrons, which are reflected mainly in the following two aspects: 1)Using the numerical relationships between the ratio of outside and inside radius in the coaxial cavity and the eigenvalues of high order mode (for TE_{mn} modes, eigenvalues are x_{mn} and TM_{mn} mode are v_{mn}), the selection of modes with different transverse indexes is provided in resonant cavity so that the competition of modes can be avoid; 2) The presence of the coaxial insert practically eliminates the restrictions of voltage depression and limiting current because the coaxial insert is fixed nearby the dynamic electronic beam [6–9]. Coaxial gyrotrons can operate stably with high order mode, which greatly improve the frequency and output power. So the study of coaxial-gyrotrons received attention. Karlsruhe Institute of Technology (KIT) (former FZK) in German first tested a corrugated coaxial gyrotron in the designed $TE_{31,17}$ mode with 1.5 MW output power at 165 GHz. On the basis of these, KIT successfully developed a corrugated coaxial gyrotron in the designed $TE_{34,19}$ mode with

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2 MW output power at 170 GHz. However, There are still many difficulties to be resolved in the study and design of coaxial-gyrotrons meeting requirements [6–9]. So going on study 170 GHz coaxial gyrotrons, and investigating the potential of its suppressing mode competition and increasing output power are significant.

In this paper the corrugated coaxial structure has be utilized and the mode $TE_{31,12}$ (JAEA also developed a conventional cylindrical-cavity 170 GHz gyrotron operating with the mode $TE_{31,12}$)that lies in a relative sparse mode spectrum has be selected finally to study and design a megawatt 170 GHz corrugated coaxial gyrotron. For the beam-wave interactions of high-order asymmetrical modes, it will take a lot of time and spend a great deal of computer resources to analyze the cold and hot cavity by commercial software (such as CST, MAGIC, etc.) so that it will not meet the needs of application study. Thus, a set of source codes has been developed and the beam-wave coupling coefficient and start oscillation current of corrugated coaxial gyrotrons have been calculated. Taking into account velocity spread and cavity wall resistivity, and basing on single mode approximation, the self-consistent beam-wave interactions of a 170 GHz MW corrugated coaxial gyrotron have been simulated and the effects of magnetic field, voltage, current, and parameters of grooves on the efficiency of beam-wave interactions were systematically study.

The rest of the paper is organized as follows. In Sec. 2, the method of mode selection is presented, and the coupling coefficient and Starting current are computed. In Sec. 3, the self-consistent nonlinear theory, modification of wave number, and effects of velocity spread are described briefly. In Sec. 4, the beam-wave interactions are simulated by a set of source codes which is based on the self-consistent nonlinear theory for coaxial gyrotrons. In Sec. 5, the Ohmic losses are studied briefly. In the last section, based on the calculation results, conclusions and summary are given.

2. Suppression of mode competition

2.1. Mode selection

In order to obtain higher output power, the radius of cavity must be increased .But with the radius of cavity increasing, the mode spectrum becomes denser. Fig. 1 shows the cylindrical waveguide TE_{mn} mode spectrum for $70 < k_{mn}R < 80$ (R is the radius of cavity and k_{mn} is the cutoff wave number), each of the vertical lines represents a possible operating mode. It can be see that each mode is in close proximity to the others, thus the competition is drastic among modes. In order to obtain stable power output, suppressing mode competition has become an important task in research of high power gyrotrons. Simultaneously utilizing all kinds of methods to suppress mode competition can achieve desired effects and selecting an appropriate mode has become a key step for suppressing mode competition. From mode spectrum (Fig. 1(b)), one can see that mode $TE_{31,12}$ lies in a relative sparse spectrum and is a high-order asymmetric volume mode ($m \geq 1$, $n \geq 2$). Selecting mode $TE_{31,12}$ as operating mode, the radius of cavity can be increased and Ohmic losses per unit area reduce. Therefore, $TE_{31,12}$ is a desired operating mode. Due to the location in dense mode spectrum, the others should compete seriously with neighboring modes and aren't desired modes. In addition to selecting desired mode, introducing longitudinal corrugations on the tapered inner conductor of coaxial resonator can further rarefy mode spectrum, enhance mode selection and suppress mode competition [8,9]. Hence, longitudinal corrugations were introduced to study in this paper.

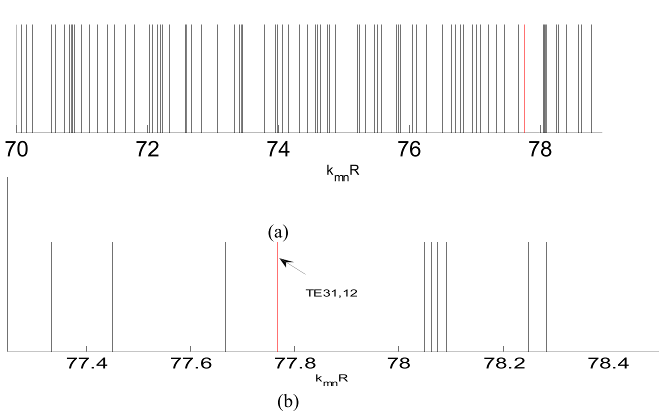

Fig. 1. Mode spectrum (a) Mode spectrum for TE_{mn} modes in cylindrical waveguide for $70 < k_{mn}R < 80$ (b) Partial enlarged view.

2.2. Coupling coefficient

By selecting an appropriate electron beam radius R_b and making operating mode obtain optimum beam-wave coupling effects is also an important method of suppressing mode competition. In a corrugated coaxial waveguide resonator, the s-th cyclotron harmonic beam-wave coupling coefficient [10,11] is

$$C_{BF} = \frac{\pi}{2}\left(N'_m(x_{mn})\right)^2 \times \frac{Z^2_{m\pm s}(x_{mn}R_b/R)}{1-\frac{m^2}{x^2_{mn}}-\left(1-\frac{m^2R^2}{x_{mn}R_{in}}\right)\left(\frac{J'_m(x_{mn})}{J'_m\left(x_{mn}\frac{R_{in}}{R}\right)+wJ_m\left(x_{mn}\frac{R_{in}}{R}\right)}\right)^2} \tag{1}$$

where $Z_{m\pm s}(x_{mn}R_b/R) = (J_{m\pm s}(x_{mn}R_b/R) - J'_m(x_{mn})/N'_m(x_{mn})N_{m\pm s}(x_{mn}R_b/R))$ is a linear combination of m-order Bessel function J_m and Norman function N_m [10–12], the signs "−" and "+" denote co-rotating and counter-rotating modes, respectively. $w = (L/S)\tan(x_{mn}d/R)$ is the surface impedance. L, S, d, and R are the width of groove, corrugated period, depth of groove and outer radius (Fig. 2), respectively. x_{mn} is the eigenvalue satisfying the following dispersion equation:

$$J'_m(x_{mn})\left[N'_m(x_{mn}R_{\text{in}}/R)+wN_m(x_{mn}R_{\text{in}}/R)\right] - N'_m(x_{mn})\left[J'_m(x_{mn}R_{\text{in}}/R)+wJ_m(x_{mn}R_{\text{in}}/R)\right] = 0 \tag{2}$$

where R_{in} is the inner radius. Selecting radius of electron beam is to make beam-wave coupling the greatest, namely to make the electronic guiding center at the maximum of RF field when gyrotrons operate with fundamental harmonic. For corrugated coaxial resonator TE_{mn} modes, it means $Z^2_{m\pm s}(x_{mn}R_b/R)$ the maximum, which the coupling coefficient is the maximum.

Fig. 2 shows the geometry of coaxial resonator [13], cross section of the coaxial resonator, unfolded scheme of the corrugated rod, projection of an electron orbit on the cross sectional plane of the resonator, and transverse field of $TE_{31,12}$ mode. Where l_1, l_2, l_3, l_4 and l_5 are five sections of resonator and θ_1, θ_2, and θ_3 are taper angles. The position of electronic movement is shown by Fig. 2(d). Where r, Ω, φ, and τ are radial position, cyclotron frequency, initial phase, and motion time, respectively.

Fig. 3 shows the beam-wave coupling coefficient of operating mode $TE_{31,12}$ and those of primary competitive modes $TE_{28,13}$, $TE_{30,12}$, and $TE_{29,13}$ in corrugated coaxial resonator. When the position of normalized radius is selected between two shown red (in

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