MODE SELECTION FOR CONVENTIONAL CAVITY BASED HIGH FREQUENCY, HIGH POWER GYROTRON

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ABSTRACT

This manuscript presents the mode selection for 240 GHz, 1 MW gyrotron for futuristic plasma fusion machines. To minimize the Ohmic wall loading and space charge effect, several very high order TE modes (m>40, p>12) are analyzed in detail. The voltage depression, Ohmic wall loading, frequency separation from the nearest neighboring modes, etc., are calculated. An in-house developed computer code GCOMS is used for the mode selection process. Simple cylindrical cavity is considered in place of coaxial cavity for 240 GHz gyrotron due to easy fabrication.

Keywords: Gyrotron, Mode selection, DEMO

I INTRODUCTION

The gyrotron is a vacuum based high power high frequency microwave device capable to deliver RF power in the range of several kilowatt to megawatt in millimeter/sub-THz wave bands [1]. This device is based on the phenomena called ‘cyclotron resonance maser (CRM) instability’, in which a gyrating electron beam interacts with the RF inside a weakly tapered interaction structure and transfer a fraction of kinetic energy to RF. Gyrotrons are used in several scientific and technological applications such as plasma fusion research, spectroscopy, material processing, etc [2]. The plasma fusion machines such as ITER, W-7X, JT-60, JET, SST-1, etc, need high power gyrotrons which can generate megawatt power (generally 1 MW per device) in the frequency range from 60 GHz to 200 GHz [2,3].

The main goal of plasma fusion research is the clean energy generation similar to nuclear fission. To achieve this goal, an experimental fusion reactor is established in the joint international collaboration named International Thermonuclear Experimental Reactor (ITER) which needs 24 MW RF power at 170 GHz frequency for electron cyclotron resonance heating (ECRH) of magnetically confined plasma. This huge amount of RF power at 170 GHz frequency can be generated only by gyrotrons. The 170 GHz gyrotrons have been developed successfully by Russian and Japanese researchers [4]. Further, to enhance the net energy yield from the plasma fusion machine (called Tokamak), the plasma confinement time and particle density should be higher (The Lawson criteria). One step ahead from ITER, the commercial plasma fusion reactors would be developed in future in which higher confinement time and particle density will be possible for the higher energy yield. Such reactors would be based on high frequency, high power and high efficiency gyrotrons (>230 GHz, 1 MW) [5].

Simple cylindrical cavity *or* coaxial cavity can be adopted as the resonator structure in high power, high frequency plasma fusion gyrotrons. Each structure exhibits some advantages and disadvantages. In case of simple cylindrical cavity (also called conventional cavity) the mode competition and space charge effect become a severe problem for high power high frequency gyrotrons due to the need of high order transverse electric (TE) mode to minimize the Ohmic wall loading at cavity walls. On the other hand in case of coaxial cavity, the space charge effect and mode competition are not the critical problems but the mechanical alignment of coaxial insert and the fabrication are challenging issues for coaxial gyrotrons. Several research and development efforts have been tried for coaxial gyrotrons, especially by German groups [6], but still the satisfactory experimental results are not achieved. In case of conventional cavity gyrotrons, a careful mode selection process of very high order TE modes can solve the problem of mode competition, space charge effect and Ohmic wall loading up to the satisfactory extent. The performance of various gyrotron components such as beam tunnel, mode launcher, RF window, collector, etc., also depends on the selected operating mode [7-9].

In this manuscript, a detail study of mode selection for conventional cavity based 240 GHz, 1 MW gyrotron is presented. The detail specifications of this gyrotron are summarized in table 1.

TABLE I. SPECIFICATIONS OF DEMO GYROTRON

Frequency	240 GHz
Output power	1 MW
Interaction efficiency	> 30 %
Ohmic wall loading	< 1kW/cm^2
Harmonic	1st
Collector type	Depressed
RF output type	Radial with mode convertor

II MODE SELECTION

The Ohmic wall loading can be defined as the amount of electromagnetic energy converted into heat at per unit cavity wall surface area. The Ohmic wall loading can be reduced by increasing the volume of cylindrical interaction cavity which is further possible by the selection of high order TE mode. Equation (1) shows the expression of Ohmic wall loading, [10].

$$\frac{dP}{dA} = 2\pi\sqrt{\frac{1}{\pi Z_0 \sigma}}\left(\frac{PQ}{L\lambda^{3/2}}\right)\left(\frac{1}{\chi_{mp}^{'2} - m^2}\right) \qquad (1)$$

Where, P, Q, L, Z_0, λ, σ, χ_{mp} and m are the RF power, quality factor, cavity length, free space impedance, wavelength, electrical conductivity of cavity material, root of Bessel function derivative for selected operating TE mode and azimuthal index for TE mode, respectively. The technical limit of Ohmic wall loading is considered < 1 kW/cm^2 [10] and thus the TE modes of m>40 and p>12 are analyzed (p is radial index). Fig. 1 shows the Ohmic wall loading for different TE modes. It is clear to minimize the Ohmic wall loading, the TE mode with higher radial index and higher azimuthal index should be selected as the operating mode.

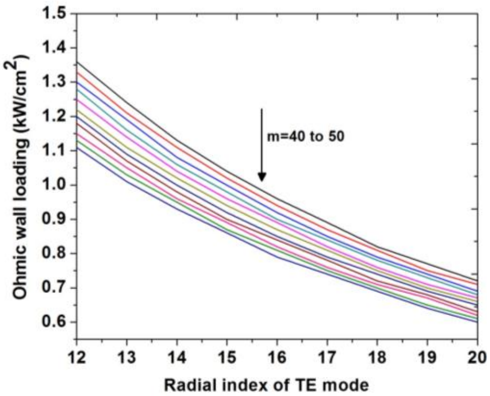

Fig. 1. Ohmic wall loading for high order TE modes (RF power= 1000 kW, cavity length= 13 mm, λ= 1.25 mm).

The space charge effect is a phenomenon of charge transportation. In case of gyrotron, the gyrating electron beam enters into the interaction cavity at the electric field maxima of the operating TE mode. The space charge effect of the gyrating electron beam can be defined in terms of voltage depression and the expression is given in equation (2) [11].

$$V_d \approx (60\Omega)\frac{I_b}{\beta_z}\ln\left(\frac{R_c}{R_b}\right) \qquad (2)$$

Where I_b, β_z, R_c, R_b are the beam current, normalized axial velocity of electron beam, cavity radius and beam radius, respectively. In case of gyrotron design, the voltage depression should be as minimum as possible because higher voltage depression degrades the beam-wave interaction efficiency [11]. Fig. 2 shows the voltage depression with respect to high order TE modes (m>40 and p>12). The voltage depression increases with radial index and decreases with azimuthal index.

For a TE_{mn} mode, $TE_{(m-3)(p+1)}$ and $TE_{(m-1),p}$ shows maximum mode competition [12]. To minimize the mode competition, the operating mode should be sufficiently far away on the frequency scale from $TE_{(m-3)(p+1)}$ and $TE_{(m-1),p}$ modes. Equations (3) and (4) show the expressions of frequency separation of operating mode from the nearest competing modes. Figs. 3 and 4 show the variation of Δf_1 and Δf_2 with respect to azimuthal and radial index of high order TE modes. For the better performance of gyrotron, Δf_1 and Δf_2 should be as higher as possible.

$$\Delta f_1 = \left(\frac{\chi'_{m,p} - \chi'_{(m-3),(p+1)}}{\chi'_{m,p}} \right) \times 100\% \qquad (3)$$

$$\Delta f_2 = \left(\frac{\chi'_{m,p} - \chi'_{(m-1),p}}{\chi'_{m,p}} \right) \times 100\% \qquad (4)$$

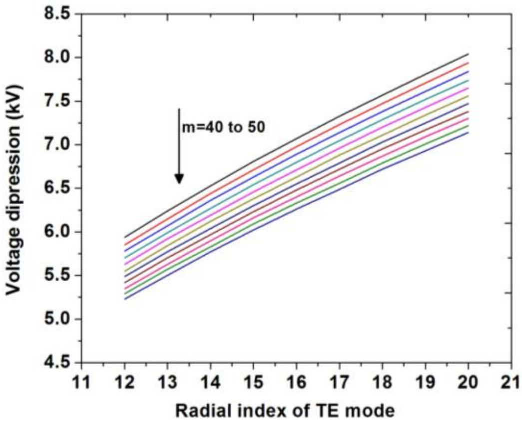

Fig. 2. Voltage depression for high order TE modes (I_b= 40 A, V_b= 90 kV, R_c= 22.66 mm, R_b= 9.53 mm).

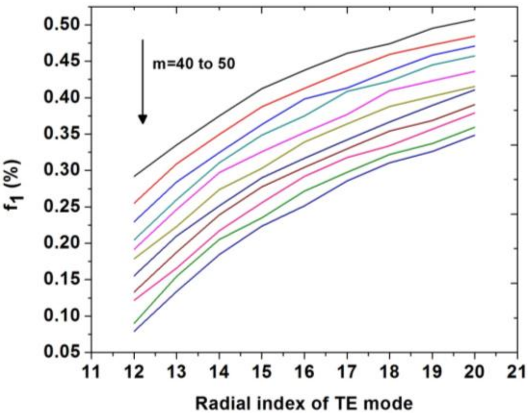

Fig. 3. Frequency separation for high order TE modes

On the basis of results shown in Fig. 1 to Fig. 4, an optimized TE mode is selected which fulfills all the technical requirements such as minimum Ohmic wall loading, voltage depression and maximum frequency separation from the competing modes. Finally, $TE_{46,17}$ is selected as the operating mode and the mode spectrum for the selected mode is shown in Fig. 5. It is clear from Fig. 5 that the operating mode $TE_{46,17}$ is well separated from its neighboring modes. Further, the study of mode competition based on linear theory [13] of gyrotron is also performed and the results are found suitable for $TE_{46,17}$ mode. In case of power and frequency growth, selected operating mode shows very good results. Tale II shows the final mode selection parameters for $TE_{46,17}$ mode.

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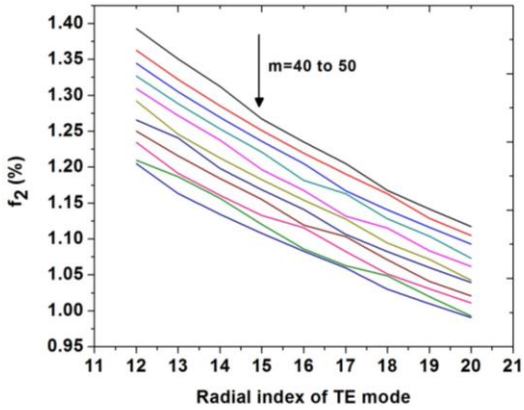

Fig. 4. Frequency separation for high order TE modes.

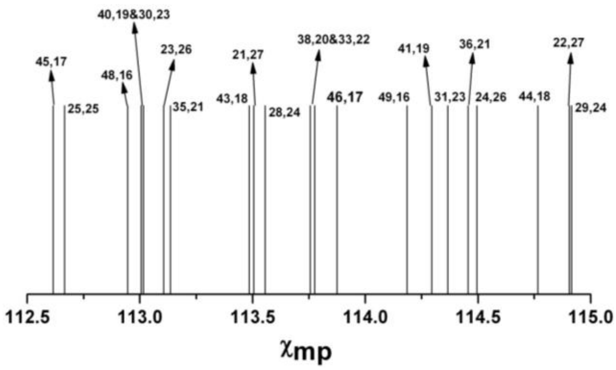

Fig. 5. Mode spectrum

TABLE II. MODE SELECTION PARAMETERS FOR $TE_{46,17}$ MODE

Operating mode	$TE_{46,17}$
Cavity radius	22.66 mm
Electron Beam Radius	9.53 mm
Ohmic wall Loading	0.79 kW/cm^2
Voltage Depression	6.79 kV
Limiting Current	66.63 A
Frequency separation (Δf_1)	0.34 %
Frequency separation (Δf_2)	1.10

III CONCLUSION

The mode selection for 240 GHz, 1 MW gyrotron is performed. Various mode selection parameters, such as, Ohmic wall loading, space charge effect, etc, are calculated for TE modes with m>40 and p>12. Based on the various mode selection parameters, $TE_{46,17}$ is selected as the operating mode for 240 GHz, 1 MW gyrotron.

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