Mode Selection For Conventional Cavity Based High Frequency, High Power Gyrotron

Pradeep Kumar[1], Chandra Mohan Negi And Raj Kumar
correspondingAUTHOR
Department Of Electronics
Banasthali Vidyapith, Newai- 304022, Rajasthan, India
E-MAILADDRESS:Pardeep.Sun@Gmail.Com

Department Of Electronics
Banasthali Vidyapith, Newai- 304022, Rajasthan, India
E-MAILADDRESS:Nchandra@Bansathali.In

Shri Vishwakarma Skill University
Palwal- 121105, Haryana, India
E-MAILADDRESS:Raj.Indiya2000@Gmail.Com

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.

KeywordsANDPHRASES.Gyrotron, Mode selection, DEMO.

1. 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]. 2020 Mathematics Subject Classification. 65C10, 65D15

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

TABLE1.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

1. 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].

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

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). Figure 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.

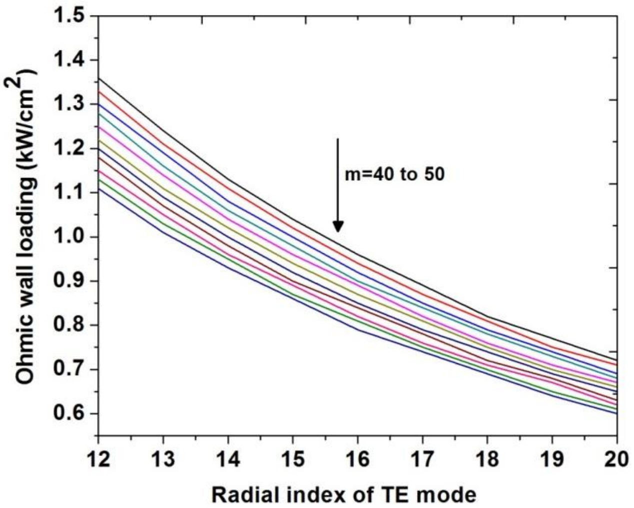


FIGURE 1.Ohmic wall loading for high order TE modes (RF power= 1000 kW, cavity length= 13 mm, λ= 1.25 mm).

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).

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

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 asminimum as possible because higher voltage depression degrades the beam-wave interaction efficiency. Figure 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. 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. Figures 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.

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

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

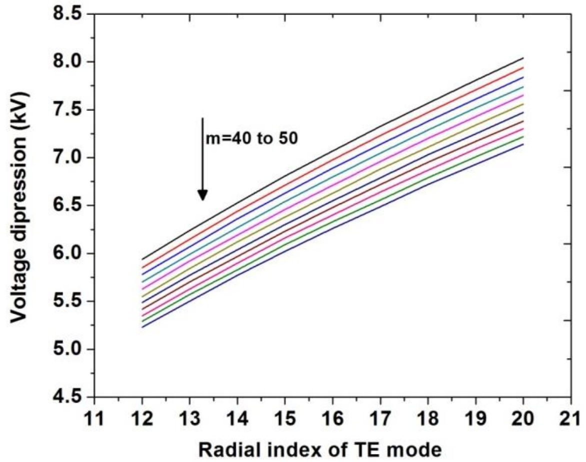


FIGURE 2.Voltage depression for high order TE modes (I_b= 40 A, V_b= 90 kV, R_c= 22.66 mm, R_b= 9.53 mm).

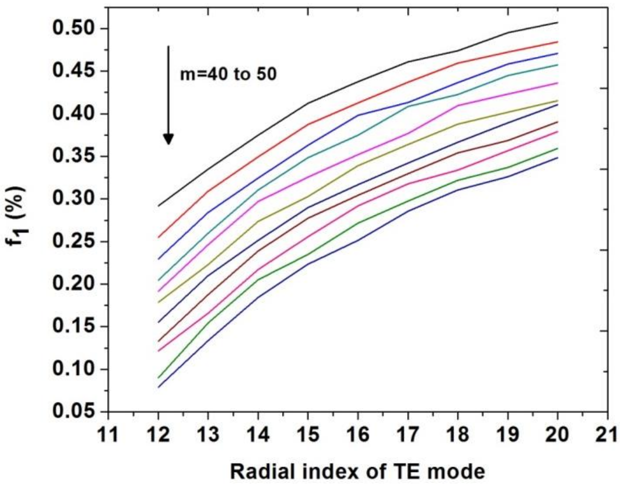


FIGURE 3.Frequency separation for high order TE modes.

On the basis of results shown in Figure 1 to Figure 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 Figure 5. It is clear from Figure 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 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.

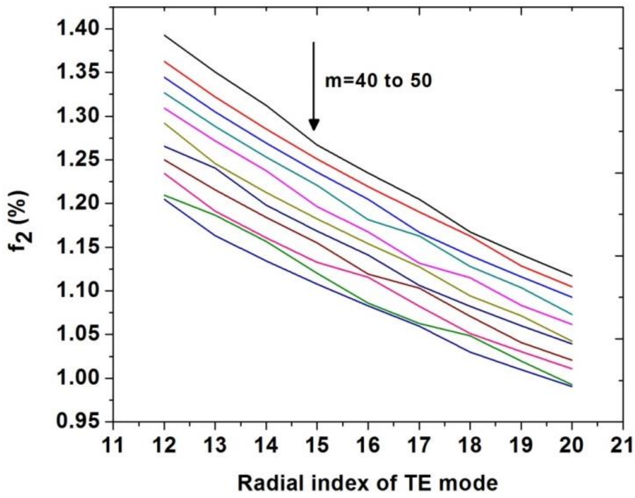


FIGURE 4.Frequency separation for high order TE modes.

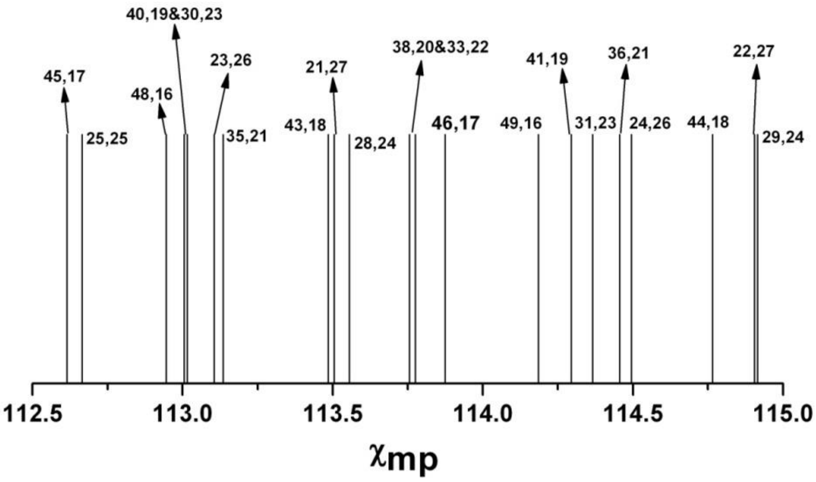


FIGURE 5.Mode spectrum.

TABLE 2.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 %

2. EFFICIENCY COMPUTATION

For the beam-wave interaction computation, a computer code is developed based on the generalized non-linear theory. This computer code calculates the variation in energy and phase of electrons along the length of cavity and finally estimates the loss in energy of electrons at the end of the cavity. Here, in the beam-wave interaction computation, total 64 electrons are considered, which are equally distributed in phase at the entrance of the cavity. The total beam power (~ 6 MW) is equally distributed among the 32 electrons. The electric field profile of Gaussian type with the peak value at the center of cavity is considered here. Oxygen free high conductive copper is considered as the cavity material. The RungaKutta method is used to solve the coupled equations shown in (1) and (2). Below is the brief description of the generalized non-linear theory used here in the beam wave interaction computation.

The beam-wave interaction computation is carried out using the self consistent generalized non-linear theory which is discussed in refs. [9,10] in detail. The following coupled equations are used in computation code:

$$\frac{du}{d\zeta} = 2Ff(\zeta)(1-u)^{n/2}\sin\theta \qquad (1)$$

$$\frac{d\theta}{d\zeta} = \Delta - u - nFf(\zeta)(1-u)^{n/2-1}\cos\theta \qquad (2)$$

where u, θ, F, ζ, Δ are normalized energy, electron phase, normalized field amplitude, normalized axial position and detuning factor, respectively. The normalized field amplitude and detuning factor are given as:

$$F = \frac{E_0}{B_0}\beta_{\perp 0}^{(n-4)}\left(\frac{n^{n-1}}{n!}\right)J_{m\pm n}\left(k_\perp R_b\right) \qquad (3)$$

$$\Delta = \frac{2}{\beta_{\perp 0}^2}\left(1-\frac{n\Omega_c}{\omega}\right) \qquad (4)$$

where E_0, B_0, β_0, Ω_c, ω, n are the electric field intensity, static magnetic field at cavity, normalized perpendicular velocity of electrons, electron cyclotron frequency, angular frequency of RF and harmonic number, respectively. The calculations are performed considering the Gaussian type of electric field profile and the integration is performed in the limit of $-\sqrt{3}\mu/2 \le \zeta \le \sqrt{3}\mu/2$.

The normalized interaction cavity length (μ) is given as:

$$\mu = \pi\frac{\beta_{\perp 0}^2}{\beta_{z0}}\frac{L}{\lambda} \qquad (5)$$

where, β_{z0}, L and λ are normalized axial velocity of electrons, cavity length and free space wavelength, respectively. The total interaction efficiency can be given as:

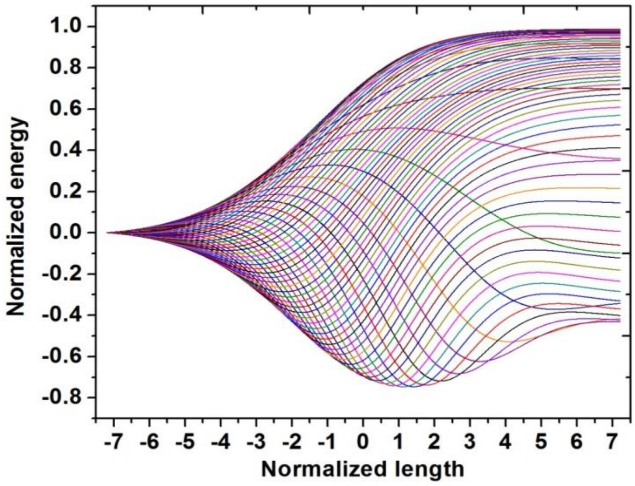
$$\eta = \frac{\beta_{\perp 0}^2}{2\left(1-\gamma_0^{-1}\right)}\eta_\perp \qquad (6)$$

where γ_0 is the relativistic factor at the cavity entrance. Further, perpendicular interaction efficiency $\eta_\perp$ is defined as:

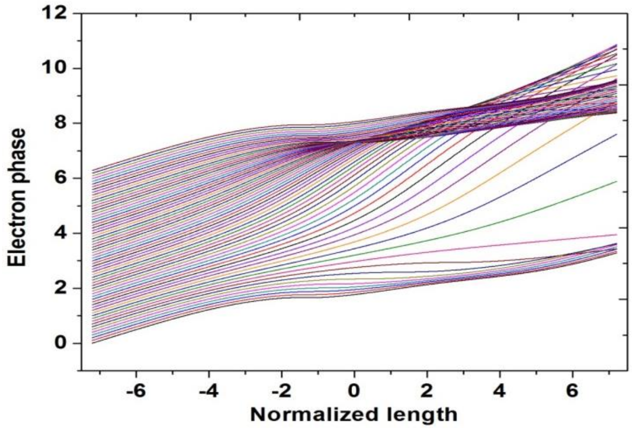
$$\eta_\perp(F,\mu,\Delta) = \left\langle u(\zeta_{out})\right\rangle_{\theta_0} \qquad (7)$$

here bracket denotes the average of particles energy at the end of interaction cavity. The coupled equations are numerically solved using Runge-Kutta method.

Figure 6 shows the energy and phase of the electrons along the cavity length. The electrons move inside the cavity and interact with the electric field of the selected TE mode. During the interaction, the kinetic energy of the electrons varies, in which majority of the electrons loss the energy in favor of the selected TE mode. Figure 5(a) shows the variation in the energy of each electron. Here it can be seen that majority of electrons are losing the energy (>0) and few are gaining (<0) from the existing electric field in the cavity. The rotation phase of the electrons directly depends on the energy and thus it also varies along the cavity as per the energy variation. Figure 5(b) shows the electrons phase along the cavity length. The interaction efficiency is estimated using the equations (6) and (7), which is 42 % for the present design.



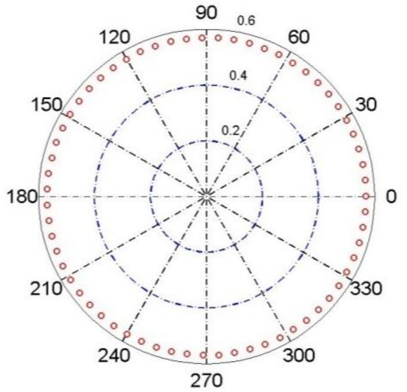
(a)



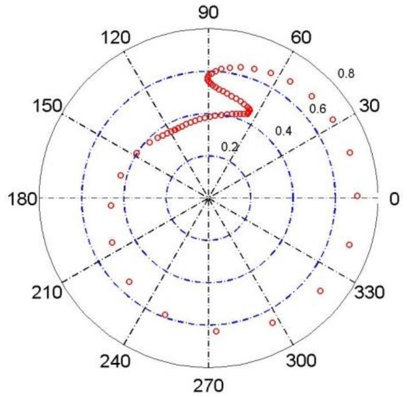
(b)

FIGURE6: (a) Normalized energy of the electrons with respect to the normalized length of the cavity, (b) Electron phase with respect to the cavity normalized length.

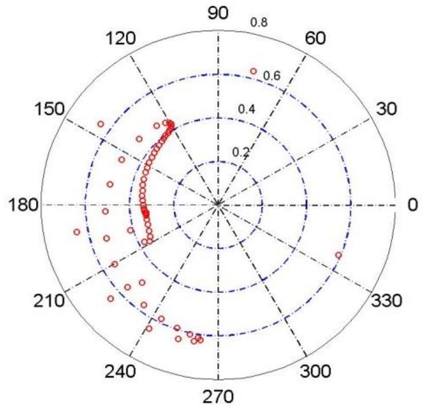
Further, Figure (7) show the azimuthal phase bunching of the relativistic gyrotrons at different axial position of the cavity. Here it can be seen that the electrons are equally distributed at the entrance of the cavity (Figure 7a). Figure 7b shows the bunch of electrons at the middle of the cavity. The gyrating radius of majority of the electrons shrinks during the beam-wave interaction while the radius of few electrons increases. It predicts that majority of electrons transfer their energy to the RF while very few are extracting from the RF field.



(a)



(b)



(c)

FIGURE7**:**The azimuthal phase bunching of electrons at different positions of the cavity.

3. 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.

REFERENCES

[1] G.S. NUSINOVICH, M. K. A. THUMM AND M. I. PETELIN, "*The gyrotron at 50: Historical review*", J. Infrared Milli. Terahz. Waves, vol. 35, pp. 325-381, 2014.

[2] N. KUMAR, U.SINGH, T.P. SINGH AND A.K. SINHA, "*A review on the applications of high power, high frequency microwave source: Gyrotron,*" J. Fusion Energy, vol. 30, pp. 257-276, 2011.

[3] M. THUMM, "*Progress in gyrotron development*", Fusion Eng. Design, vol. 66–68, pp. 69-90, 2003.
[4] M. THUMM, "*State of the art of high power gyro-devices and free electron masers update 2014*", FZK, KIT, Germany, 2014.
[5] E. POLI, G. TARDINI, H. ZOHM, E. FABLE, D. FARINA, L. FIGINI, N.B. MARUSHCHENKO AND L. PORTE, "*Electron-cyclotron-current-drive efficiency in DEMO plasmas*", Nucl. Fusion, vol. 53, p. 013011 (10pp), 2013.
[6] O.DUMBRAJS, "*Coaxial gyrotrons: past, present, and future (review)*", IEEE Trans.Plasma Science, vol. 32,pp. 934 – 946, 2004.
[7] N. KUMAR, U. SINGH, A. KUMAR, H. KHATUN, A.K. SINHA, "*On the design of a high-efficiency double-beam gyrotron*", IEEE Trans. Plasma Science, vol. 39, pp. 1781-1785, 2011.
[8] A. KUMAR ET AL, "*Integrated design of undepressed collector for low power gyrotron*", Journal of Infrared, Millimeter, and Terahertz Waves, vol. 32, pp. 733-741, 2011.
[9] U. SINGH, N. KUMAR AND A.K. SINHA, "*Gyrotron and its electron beam source: A review*", Journal of Fusion Energy, vol. 31, pp. 489-505, 2012.
[10] N. KUMAR, A. KUMAR, U. SINGH, T. P. SINGH AND A. K. SINHA, "*Thermal and Structural Analysis of Interaction Cavity and Its Effect on the Operating Mode Excitation for a 120GHz, 1MW Gyrotron*", Int. J. Thermophys, vol. 32, pp. 1038-1046, 2011.