PARAMETRIC STUDY OF SPACE CHARGE EFFECT IN COAXIAL CAVITY

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ABSTRACT

A detail parametric study of space charge effect related to coaxial insert of 2 MW, 140 GHz coaxial gyrotron is discussed in this manuscript. Corrugation is done in the coaxial insert to minimize the Ohmic wall loading. The geometry of corrugated coaxial insert seriously affects the space charge effect in a gyrotron. Space charge effect is very critical especially for multi-megawatt high frequency gyrotrons. Considering all these facts,a detail parametric study of coaxial insert is performed for 140 GHz coaxial gyrotron in this article.

Keywords: *Coaxial, space charge effect, coaxial insert*

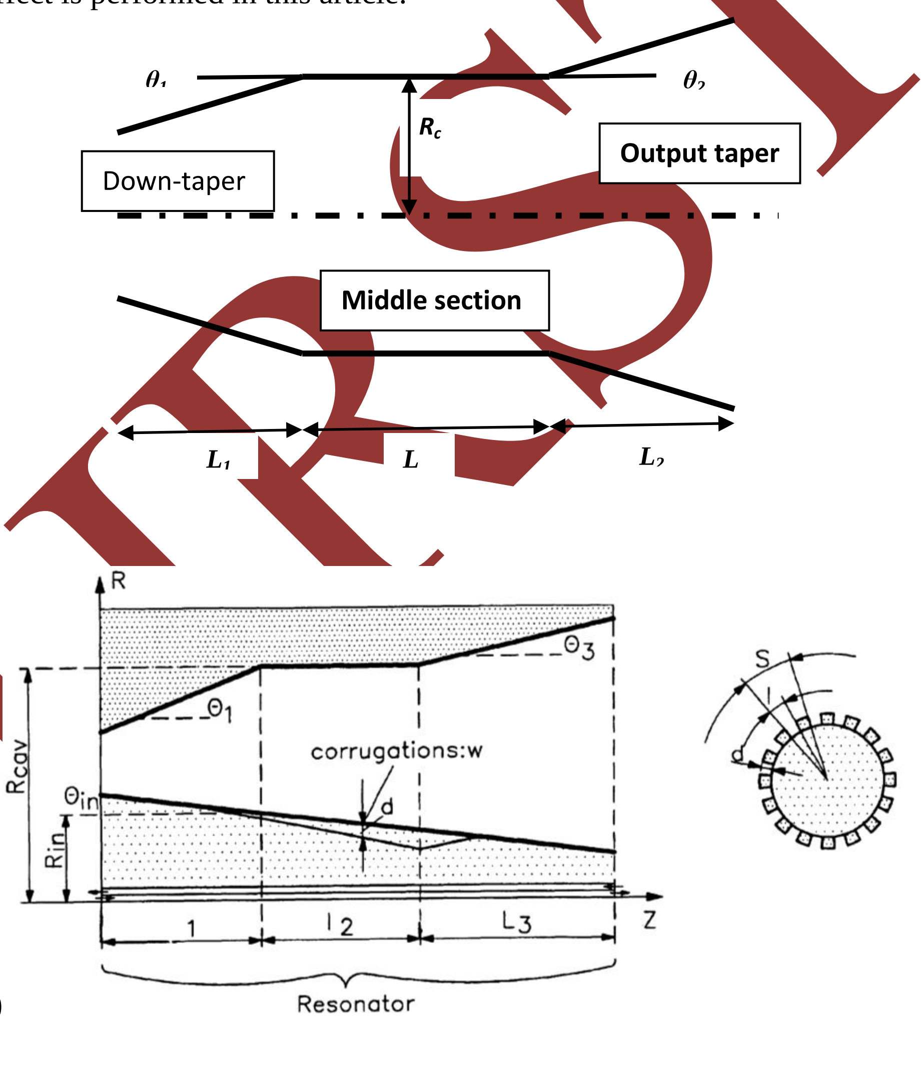
INTRODUCTION

Gyrotron is a device used for the generation of high power electromagnetic radiation in millimeter and sub-THz wave band. This device was invented in Russia in the decade of 1960 for the plasma fusion application [1]. At present, rather than plasma fusion, gyrotron has wide applications in other field of science and technology such as spectroscopy, medical science, defense, communication, material processing, etc., [2,3]. This device is based on a phenomena called 'cyclotron resonance maser instability', in which weakly relativistic gyrating electron beam interacts with the RF inside a tapered cylindrical cavity and transfer a friction of beam kinetic energy to RF via the 'azimuthal relativistic phase bunching' [4-6].

At present, gyrotron is a signature device in plasma fusion and almost each plasma fusion system (tokamak as well as stellarator) uses gyrotron as a high power radiation source. Such gyrotrons are called fusion gyrotrons and these devices differ than other low power or high frequency gyrotrons. Major features of fusion gyrotrons are very high RF power (> 1 MW), high frequency (> 100 GHz), and high efficiency (> 40 %). To achieve these features, very high order transverse electric (TE) mode is selected as the operating mode for fusion gyrotron [7]. One major part of any gyrotron is the interaction cavity where the beam-wave interaction takes place. In general, simple cylindrical open interaction cavity (Fig. 1a) is used for MW class millimeter wave gyrotrons. The interaction cavity in gyrotron consists three parts (as shown in Fig. 1a), down taper (cut-off region), middle section and up-taper section (travelling wave region). In case of much higher RF power (*e.g.* 2 MW or more), the cylindrical open interaction cavity starts to show serious problem of ohmic wall loading as well as space charge effect [8,9]. High beam current is required to get much higher RF power, which further enhances the space charge effect of the transported electron beam. Considering this issue in multi-MW gyrotrons, the coaxial insert is used in the cylindrical cavity (Fig. 1b) and this whole structure is called coaxial cavity. The detail discussion on coaxial cavity is performed in a review article [10].

Here in this article, the parametric study of space charge effect in coaxial cavity of 140 GHz, 2 MW gyrotron is performed. Table 1 shows the design parameters of 140 GHz coaxial gyrotron. The voltage depression, limiting current, ohmic wall loading at cavity wall and at different part of coaxial insert are major design parameters of the coaxial cavity. The detail discussion on space charge effect is performed in this article.

(a)



(b)

Fig. 1: (a) simple cylindrical cavity, **(b)** Coaxial cavity [10].

Table 1: Design specifications of coaxial 140 GHz gyrotron

Frequency	140 GHz
Power	2 MW
Interaction efficiency	>30 %
Beam voltage	90 kV
Beam current	70 A
Alpha	1.3
Operating mode	$TE_{31,17}$

SPACE CHARGE EFFECT

The space charge effect is a common phenomenon in the charge transportation. The effect is created due to the potential of the transported charge beam. The space charge effect critically depends on the charge transportation geometry and the structure geometry through which the charge is moving. The space charge effect can be defined in terms of the voltage depression (V_d) and the limiting current (I_L). The electrons emitted from the cathode gain kinetic energy from the applied electric field produced by the accelerating voltage V_{ac} as they move towards the resonator. Due to the space charge of the electron beam, a negative potential is created which screens the electrons partially from the accelerating voltage. This effect is known as voltage depression. For the coaxial cavity gyrotron, the expressions for voltage depression and limiting current are given in equations (1) and (2) [9, 11].

$$\Delta V = 60.\frac{I_b}{\beta_z}\ln\left(\frac{R_c}{R_b}\right)\frac{\ln\left(R_b/R_i\right)}{\ln(R_c/R_i)} \qquad (1)$$

Here, I_b, R_c, R_b, and β_z are the beam current in amperes, cavity radius, beam radius and normalized axial component of electron beam velocity. The limiting current can be defined as the amount of beam current which can be transported through the interaction cavity.If the beam current above the limiting current value is pumped in the cylindrical cavity, the voltage depression becomes so high that the mirroring occurs in the electron beam where the normalized axial velocity of the electrons (β_z)→0.

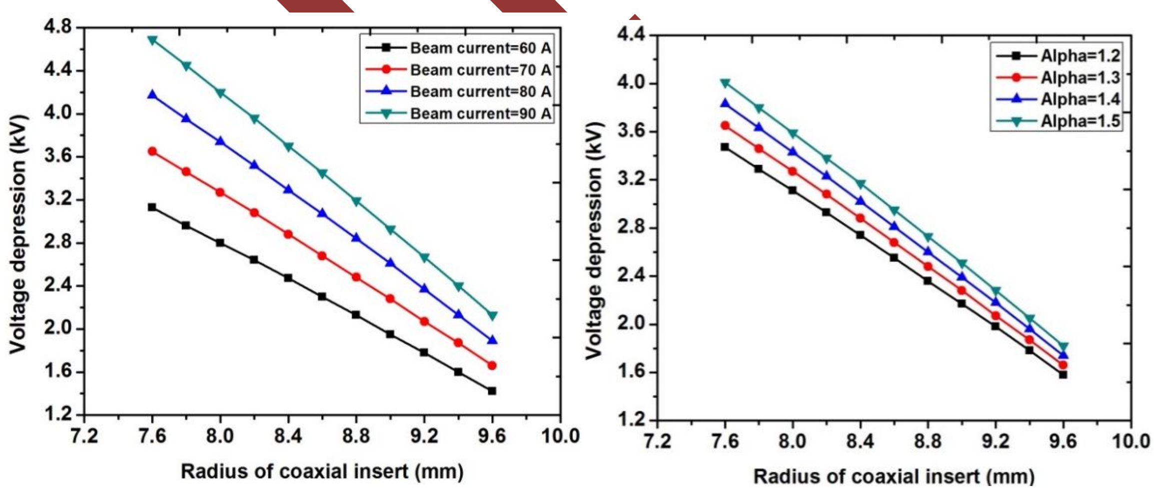
$$I_L = 17070.\frac{\gamma\left(\frac{\beta_z}{\sqrt{3}}\right)^3}{2\ln\left(\frac{R_c}{R_b}\right)\frac{\ln\left(R_b/R_i\right)}{\ln\left(R_c/R_i\right)}} \qquad (2)$$

where $R_b = \chi_{m\pm s,i}\frac{\lambda}{2\pi}$, $R_c = \chi_{m,p}\frac{\lambda}{2\pi}$ and R_i is radius of coaxial insert.

For any gyrotron (simple cylindrical cavity or coaxial cavity), the voltage depression reduces the value of the applied beam voltage which further affects the efficiency of beam-wave interaction. Equations (1) and (2) can be reduced to equations of voltage depression and limiting current [12] for simple cylindrical cavity by putting R_i=0, *i.e.* no coaxial insert. It can be seen from equation (1), the voltage depression becomes maximum for R_i=0 (for simple cylindrical cavity) and ΔV reduces sharply with R_i. Vice versa in limiting current, I_L enhances sharply with R_i. For any gyrotron design, the voltage depression should be as minimum as possible and limiting current should be as maximum as possible. Further, the cavity radius and beam radius directly depends on the selected operating mode (χ_{mp} is the root of Bessel function derivative, which is a parameter of TE_{mp} mode). So in conclusion it can be said that the voltage depression and limiting current in cavity directly depends on the operating mode. Various TE modes are analyzed in terms of voltage depression and limiting current and finally $TE_{31,17}$ mode ($\chi_{mp=}$94.615) is found suitable.

RESULTS AND DISCUSSION

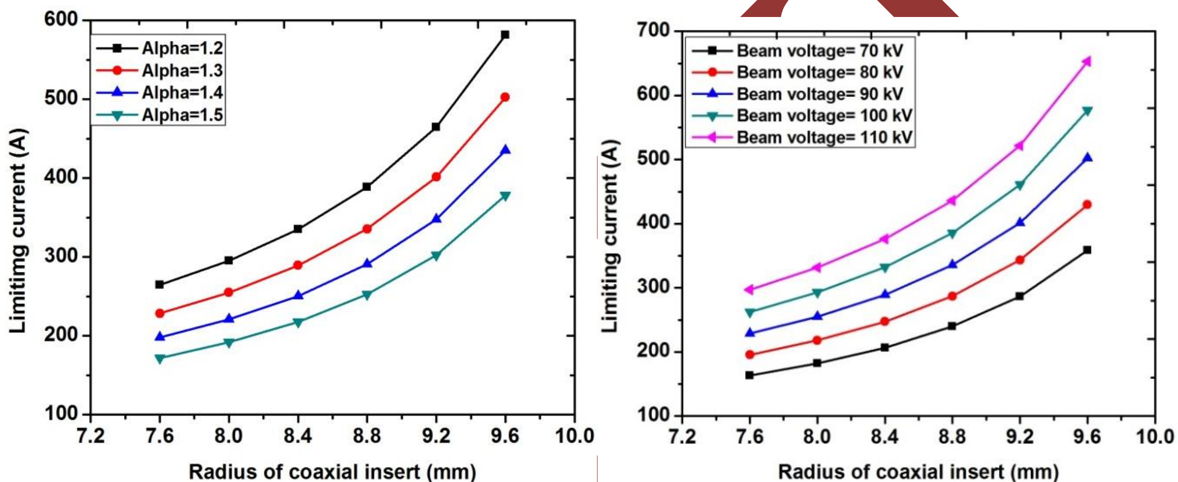
Fig. 2 shows the results of voltage depression with respect to radius of coaxial insert (R_i), velocity ratio of electron beam (α) and beam current (I_b). Voltage depression (ΔV) is the voltage created by the hollow cylindrical electron beam (used in gyrotron) which always reduces the applied accelerating voltage. So, higher voltage depression degraded the beam-wave interaction efficiency. One major cause to put a coaxial insert in the middle of simple cylindrical cavity is to reduce the voltage depression and to enhance the limiting current so that for multi-megawatt generation of RF power, much higher electron beam current can be pumped into the interaction cavity.



(a) (b)

Fig. 2: Voltage depression with respect toR_i **(a)** for different values of beam current, **(b)** for different values of alpha.

Equation shows, ΔV is directly depends on beam current (potential always depends on amount of charge), which is also reflected in Fig. 3a. Further, depression is inversely depends on the radius of coaxial insert. The radius of coaxial insert cannot be greater than the acoustic radius corresponding to the operating TE mode. For higher value of alpha, voltage depression is also becomes higher. The reason behind it is for higher alpha, axial velocity of electron beam reduces which directly affects the voltage depression. Limiting current (I_L) is a parameter which describes that how much beam current can transport through the interaction cavity. Fig. 4 shows the results of limiting current with respect to radius of coaxial insert, alpha and beam voltage. For the efficient performance of gyrotron device, the voltage depression should be less than of 10 % of beam voltage and the limiting current should be more than twice of beam current.



(a) **(b)**

Fig. 3: Limiting currentwith respect toR_i**(a)** for different values of alpha, **(b)** for different values of beam voltage.

Table 2: Voltage depression and Limiting current.

Cavity radius (R_c)	32.28 mm
Cavity length (L)	23 mm
Coaxial insert radius (R_i)	8.5 mm
Voltage Depression	2.9 kV
Limiting current	285 A

CONCLUSION

In this article a detail parametric study of space charge effect in coaxial cavity is performed. Interaction cavity design parameters such as voltage depression and limiting currentare calculated with respect to coaxial insert geometry. Based on the constraints of space charge effect the geometry of coaxial insert is finalized for 2 MW, 140 GHz gyrotron coaxial cavity operating at $TE_{31,17}$mode.

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