Gyrotron Development at High Order Modes

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Abstract

The present work has been characterized by higher order modes in the cavities of the Gyrotron; they are capable of producing RF plasma by developments of it. It uses for fusion systems. We choose the TE_{31,8} mode in our study. The main problem of gyrotron is the device of the thermal cavity loading. The problem of the thermal loading is solved when any parasitic modes suppress, absence of desired modes; the thermal loading is increased when the high power tube of gyrotron operation is unstable. The mathematical interaction model contains equations that describe the electron motion and the field profiles of the transferred electric modes of the resonator, these are interacting with electrons based on the finite difference method that has been designed to study the starting current, the frequency, quality factor and calculates the roots of the Bessel function by the program we designed in Fortran language. They are used to calculate the operation frequency. Good agreement is between our results and the previous published results both confirm the accuracy of the performance of the designed program.

Keywords: developed gyrotron, high order mode, RF plasma.

1. Introduction

The gyrotron is a microwave source capable of producing high power through the interaction between the beam and the wave.[1] convert the kinetic energy of electrons into radiation. as shown in Figure(1). The gyrotron oscillator consists of these components: a gun oscillator is used as a microwave source. It operates at a frequency of (670) GHz and releases a power of approx. (11W), interaction circuit (cavity), magnetic field source (magnetic or solenoids), spent electron beam collector, output taper and window. In the injection gun, a magnetron is generated annular electron beam; it is focused into an open...
cavity resonator with the axial magnetic field. In the cavity of this tube, the kinetic energy is converted into an RF from the beam. Finally it is converted into a Gaussian beam. Then the spent beam is collected at the collector, to produce high powers at millimeter wavelengths. We choose a high order cavity mode such as TE_{31,8}-TE_{10,6}-TE_{8,5}. To compensate for the high wall losses in the cavity at a high frequency the modern gyrotron development during the last three or four years. One may notice that several principal steps we made in the development of the megawatt power gyrotron:

1. At a very high order volume modem, solve the problem of thermal cavity loading in gyrotron.
2. Demonstration of the depressed collector to solve gyrotron collector and power supply problems.
3. The windows are made of artificial diamond discs. These three points important to be used in the gyrotron in the plasma experiment.[2,3]

![Figure 1. Schematic simple of oscillator (gyrotron) [1]](image)

In the past years, Danly et al. report using a novel quasi–optical output antenna. The first experiment on 100 GHz and power (200 kW) are discussed by Bensimhon et al. and show the stable operation is possible with a high – order mode, complex interaction cavity. Saito et al. designed a 137 GHz gyrotron for plasma scattering. [4]

Jagadishwar Sinigin [5] in 1999 presented the theory and design of gyrotron-traveling wave amplifiers at millimeter wave frequencies suitable for long distance communication and radar. The design goals for the tube were 100 kW peak power at 140 GHz and 30% efficiency.

In 2002, Edith Borie et al. [6] studied the operation of multi-frequency and a 149 GHz gyrotron was designed to operate in the high order mode at high frequency in GHz.

The design of an 8 mm TE_{13} mode gyrotron was given by Wenxiany, Wang et al. [7]. Tsai, et al. [8] in 2004 presented a theoretical study of fundamental cyclotron harmonic gyro-TWT at TE_{01} mode, with distributed wall losses. The initial theoretical, [8] in 1996
reported the short-and-long pulse operation of a \( TE_{10.4} \) mode and the experiment configuration of the tube was described.

2. Numerical method

We get Bessel’s equation with Bessel function \( J_m(r) \) by using a method of variable separation. We considered wave propagation on a cylindrical waveguide, as shown in Fig. 1[9].

The longitudinal electric and magnetic fields \( E_z \) and \( H_z \), in a circular waveguide are:

\[
    H_z = c_m J_m(k_c r) \sin \sin (m\phi) \\
    E_z = c_m J_m(k_c r) \cos \cos (m\phi)
\]  \hspace{1cm} (1)

\[
    E_\phi = \frac{1}{k_c} \left[ jmk_z c_m J_m(k_c r) \sin \sin (m\phi) + j\omega k_c J_m(k_c r) \cos \cos (m\phi) \right] \\
    H_\phi = \frac{1}{k_c} \left[ jmk_z c_m J_m(k_c r) \cos \cos (m\phi) + j\omega k_c J_m(k_c r) \cos \cos (m\phi) \right]
\]  \hspace{1cm} (2)

Where \( c_m \) and \( c_m' \) denote the coefficients of fields, \( r \) the radial distance, \( J_m(k_c r) \) is called the Bessel function of the first kind, and \( m \) is the order of the Bessel function. Substituting these equations into the Maxwell equation, we get field components in terms of \( E_z \) and \( H_z \) in circular waveguide [9].

\[
    E'(r, \phi, z) = E(r, \phi) \exp[i(\omega t - k_z z)]
\]  \hspace{1cm} (5)

Where \( t \) represents the time and \( \omega \) the angular frequency.

3. Design of cavity

In (28-170GHz), the magnetron gun produced an annular beam and transported it to the cavity [10, 11]. In the middle cavity reach the interaction between the electron beam and RF wave when RF fields peak values. The waveguide is closed by a pinhole diaphragm, through which part of the generated microwave power escapes. The interaction efficiency is defined as: [12]

\[
    \eta_{int} = \left[ \frac{\alpha^2}{2(1 - \gamma_0^{-1})} \right] \eta_{\perp}
\]  \hspace{1cm} (6)

Where \( \eta_{\perp} \) is the orbital efficiency \( \alpha \), is the ratio between initial orbital velocity normalized and the speed of light, \( \gamma_0 \) is the Lorentz factor. The orbital efficiency is the fraction of the energy of electro gyration transformed into electromagnetic radiation.

\[
    P_{out} = \left( \frac{\omega}{Q_D} \right) W
\]  \hspace{1cm} (7)

\[
    P_{\Omega} = \left( \frac{\omega}{Q_{\Omega}} \right) W
\]  \hspace{1cm} (8)

Where \( W \) is the energy stored in the cavity, \( Q_D \) is the diffractive Q-factor and \( Q_{\Omega} \) is the ohmic quality factor of the \( TE_\perp \) modes.
From Eq. (7,8) These are power inversely proportional to the diffractive and ohmic quality factors.[13]

\[ Q_{\Delta} = \left( \frac{R_W}{\delta} \right) \left( 1 - m^2 \right) \frac{1}{X_{m,n}^2} \]  

(9)

Where \( R_W \) is the cavity radius, \( m \) is the azimuthal index of the mode, \( n \) is the radial index, \( X_{m,n} \) is eigen number and \( \delta = \frac{1}{\sqrt{\pi f \sigma \mu_0}} \) where \( \sigma \) is the conductivity of the cavity wall. The cut off region, prevents backward waves towards the gun. Plasma will be formed in the breakdown region. When the electron density is high enough, a significant part of the wave beam should be reflected from dense plasma, where plasma fillmentation in a gyrotron focused wave beam was observed [13,14]. The plasma density inside the volume is approximate by [15].

\[ n = n_o \exp(v_{i,eff}) \]  

(10)

Where \( v_{i, eff} \) is the effective ionization frequency and is dependent on the power density over power threshold density. The quality diffraction is changing with a length of the cavity and the wavelength.[16]

\[ Q_{diff} \alpha \left( \frac{L}{\lambda} \right)^2 \]  

(11)

The relation (11) leads to increased ohmic losses in the cavity by equ.(12)

\[ \eta \alpha \frac{Q_{omic}}{Q_{dif} + Q_{ohm}} \]  

(12)

Where \( \eta \) is the total efficiency.

4. Results and Discussion

The quality factor is depends on cavity sizes and the parameters of the electron beam, it is very critical parameters for the thermal loading of the cavity, to get on high gyrotron efficiency and reducing the ohm losses for TE_{31,8} mode at a frequency of 670 GHz the wall radius is 4.477mm, power is enhanced with cavity size increase, typical Q_{D}-factor for fusion gyrotron is 1000-1500, Q_{ohm}-factor depend on the cavity size and wavelength. We describe the interaction of wave-particle by the computer program (Gyro).This code uses the forward finite difference technique as a numerical method for solving all governing differential equations in three dimensions (r,\( \phi \),z). The input data of the program that beam voltage, the external magnetic field, normalized cavity length, the velocity ratio, energy, the mode number (m,n,l), and root of Bessel \( X_{mnl} \). This code calculates the power, efficiency, quality factor and beam current in the tube with a single cavity show this result in a Table.1.

| Table 1. Reported and calculates results of design parameters of a 670-GHz. |
|--------------------------------------------------|------------------|------------------|
| **TE_{31,8}**                                   | **Our Results**  | **Ref [13]**     |
| Beam voltage (kV)                               | 71               | 70               |
| Axial velocity ratio                            | 1.3              | 1.3              |
| Normalized length                               | 10               | 10               |
| The frequency (GHz)                             | 671              | 670              |
| Radius of the cavity (mm)                       | 4.54             | 4.54             |
Table 2. Reported and calculates results of design parameters of a 670-GHz.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Our Results</th>
<th>Ref.[10, 11]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_b$ (kV)</td>
<td>71</td>
<td>72.5</td>
</tr>
<tr>
<td>$L/\lambda$</td>
<td>5.5</td>
<td>6.4</td>
</tr>
<tr>
<td>$I_b$ (mA)</td>
<td>70</td>
<td>50-70</td>
</tr>
<tr>
<td>$Q_{\text{diff min}}$</td>
<td>1123</td>
<td>1200</td>
</tr>
<tr>
<td>Axial velocity ratio</td>
<td>1.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The quality factor given by equation (11) for $TE_{mnl}$-mode[18] is represented graphically in Figure 2

$$Q\frac{\delta}{\lambda} = \frac{\left[1 - \left(\frac{m}{X_{mn}}\right)^2\right]\left[X_{mn}^2 + P^2 R^2\right]^3}{2\pi \left[X_{mn}^2 + P^2 R^3 + \left(1 - R\right)\left(P R m X_{mn}\right)^2\right]}$$  \hspace{1cm} (11)

Where $R = D/L$, $P = l\pi/2$ and $Q\frac{\delta}{\lambda}$ is the quality factor a function of the cavity dimensions. Those curves in fig.2 correspond to simulation results of Gaussian Profiles. In this figure, we see a maximum of $Q\frac{\delta}{\lambda}$ when the diameter equal the length because the minimize losses.

![Figure 2. QD/L for $TE_{31,8}$ mode in the cavity.](image)

To study the relation between $(B_0D)^2$ and $(D/L)^2$ for $TE_{31,8}$ mode, we used Eq.12 [18] as shown in fig.3.

$$(B_0D)^2 = \left(\frac{\gamma cm_e}{e}\right)^2 \left[4X_{mn}^2 + \pi^2 l^2 \left(\frac{D}{L}\right)^2\right]$$  \hspace{1cm} (12)
Figure 3. The relation between \(B_0D\) and \((D/L)^2\) for TE\(_{31,8}\) mode.

We calculated the starting currents by depending on the equation (13) as [19]

\[
I_S = -1.5608 \times 10^{-21} \frac{\gamma \omega v_\perp^2 l^2 r_0^2}{Q} \frac{x_{mn}^2}{L} \frac{j_{m+1}^2 (X_{mn} r_0/r) + j_{m-1}^2 (X_{mn} r_0/r)}{G - B_\perp^2 \omega_c \frac{dG}{2K_z V_x \, dX}} (AMP) \tag{13}
\]

Where \(B_\perp = \left(v_r^2 + v_\phi^2\right)^{\frac{1}{2}}/C\), \(X = (\omega_c - \omega)/K_z V_x\)

And

\[
G = -\frac{1}{2} \left[ (-1)^l \cos \cos (l\pi x) - 1 \right]/(x^2 - 1)^2
\]

From fig.4 the starting current of TE-mode was calculated as a function of magnetic field, when a minimum starting current for excited a single-mode in the interaction region. It is smaller if the magnetic field increased until reaching a point where it rises abruptly.

Figure 4. Start oscillation current of cavity TE\(_{31,8}\).

The operating modes are set in the cavity resonator and we could predict the radius of this cavity by mode chart Figures (5,6,7). We can estimate that the magnetic field is required to excite the TE\(_{mn}\)-mode of interest.
5. Conclusions

The present paper studies the status of gyrotron development on average power achievements. A plasma heating like magnetic fusion experiments depend on the parameter average power to produce electric power. The system is usually desired with a duty factor
typically 10% for radar application, the gyrotron oscillator developers in at frequencies in GHz and high power in megawatt.

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References


