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Gyrotron Development at High Order Modes

Luma Y. Abbas
Department of Physics, College of Science, The University of Mustansiriyah, Baghdad, Iraq.
lmaphysics2203@gmail.com

Nedal ali Hussain
Department of Physics, College of Science, The University of Mustansiriyah , Baghdad, Iraq.
nidalali44@yahool.com

Ali N . Mohammed
Department of Physics,College of education, The University of Mustansiriyah,Baghdad, Iraq.
aliphysics2203@gmail.com

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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]

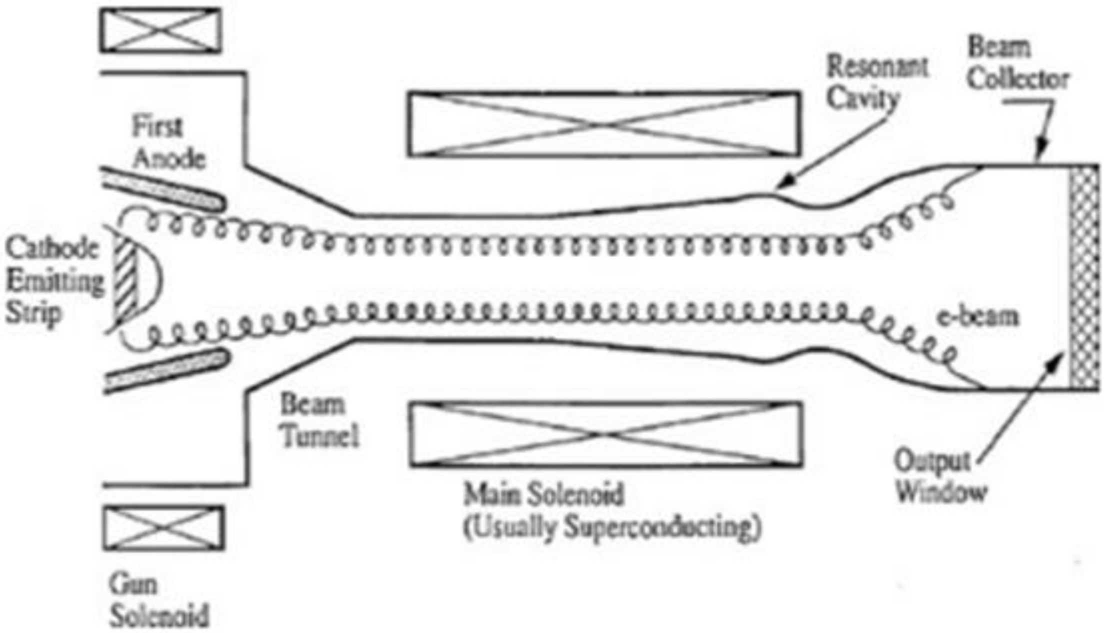

Figure 1. Schematic simple of oscillator (gyrotron) [1]

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:

$$H_z = c_m^{`} J_m(k_c r) \ sin\, sin\,(m\phi) \qquad (1)$$

$$E_z = c_m J_m(k_c r) \ cos\, cos\,(m\phi) \qquad (2)$$

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. Subsitituting these equations into the Maxwell equation, we get field components in terms of E_z and H_z in circular waveguide [9].

$$E_\emptyset = \frac{1}{k_c}\left[\frac{jmk_z}{r} c_m J_m(k_c r)\, sin\, sin\,(m\emptyset) \ + j\omega\mu k_c' J_m' \,cos\,(k_c r) cos\,(m\emptyset)\right] \qquad (3)$$

$$H_\emptyset = \frac{1}{k_c}\left[\frac{jmk_z}{r} c_m' J_m(k_c r)\, cos\, cos\,(m\emptyset) \ + j\omega\varepsilon k_c J_m' \,cos\,(k_c r) cos\,(m\emptyset)\right] \qquad (4)$$

Where C_m, C_m' are the coefficients of longitudinal field, K_c is the wave number, is the propagation constant, r is the radial distance, $J_m(k_c r)$ is called the Bessel function, $J_m'(k_c r)$ is the derivative, and m is the order of the Bessel function.

$$E(r, \emptyset, z) = E(r, \emptyset) exp[i(\omega t - k_Z)] \qquad (5)$$

Where t represents the time and ω 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]

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

Where $\eta_\perp$ is the orbital efficiency α, is the ratio between initial orbital velocity normalized and the speed of light, γ_0 is the Lorentz factor. The orbital efficiency is the fraction of the energy of electro gyration transformed into electromagnetic radiation.

$$P_{out} = \left(\frac{\omega}{Q_D}\right) W \qquad (7)$$

$$P_\Omega = (\left(\frac{\omega}{Q_\Omega}\right) \mathrm{W} \qquad (8)$$

Where W is the energy stored in the cavity, Q_D is the diffractive Q-factor and Q_Ω is the ohmic quality factor of the TE_ modes.

From Equ. (7,8) These are power inversely proportional to the diffractive and ohmic quality factors.[13]

$$Q_{\Omega} = \left(\frac{R_W}{\delta}\right)\left(\frac{1 - m^2}{X_{m,n}^2}\right) \tag{9}$$

Where R_W is the cavity radius, m is the azimuthal index of the mode, n is the radial index, Xmn is eigen number and δ is skin depth. $\delta = \frac{1}{\sqrt{\pi f \sigma \mu_0}}$ where σ 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 fill mentation in a gyrotron focused wave beam was observed [13,14] . The plasma density inside the volume is approximate by [15].

$$\text{n}= n_o exp(v_i, efft) \tag{10}$$

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]

$$Q_{diff} \alpha (\frac{L}{\lambda})^2 \tag{11}$$

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

$$\eta \alpha \frac{Q_{omic}}{Q_{dif} + Q_{ohm}} \tag{12}$$

Where η 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,∅,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, 2**.

Table1. 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.

$TE_{31,18}$-Mode	Our Results	Ref.[10, 11]
V_b (kV)	71	72.5
L/λ	5.5	6.4
I_b (mA)	70	50-70
$Q_{dif,min}$	1123	1200
Axial velocity ratio	1.4	1.4

The quality factor given by equation (11) for TE_{mnl}-mode[18] is represented graphically in **Figuer2**

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

Where R=D/L , P=lπ/2 and $\frac{Q\delta}{\lambda}$ 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 $\frac{Q\delta}{\lambda}$ when the diameter equal the length because the minimize losses.

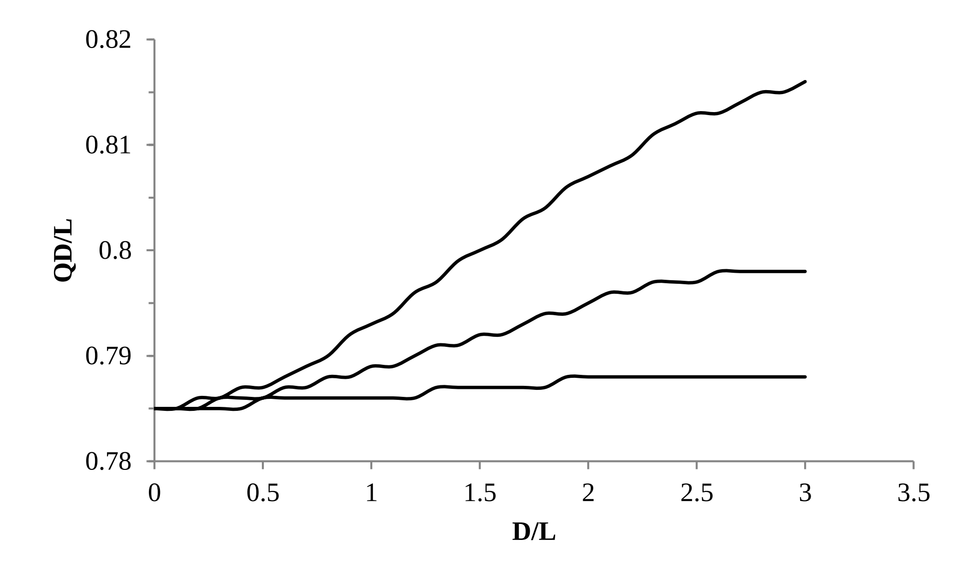

Figure 2. QD/L for $TE_{31,8}$ mode in the cavity.

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.

$$(B_0D)^2=\left(\frac{\gamma c m_e}{e}\right)^2\left[4x_{mn}^2+\pi^2 l^2\left(\frac{D}{L}\right)^2\right] \qquad (12)$$

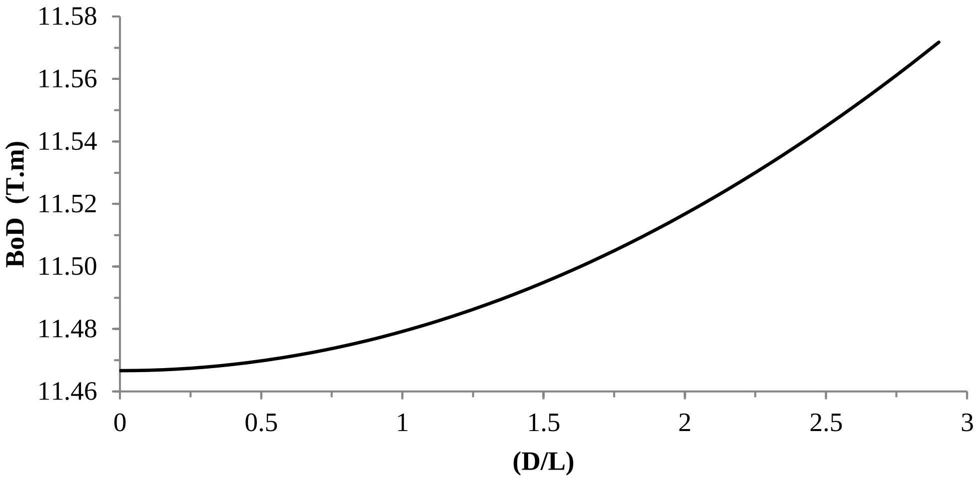

Figure 3. The relation between(B_0D) and $(D/L)^2$ for $TE_{31,8}$mode.

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

$$I_S = -1.5608 \times 10^{-21} . \frac{\gamma \omega v_z^2}{Q} \frac{l^2 r_w^2}{L} \frac{\frac{(X_{mn}^2 - m^2)}{X_{mn}^2 \left[J_{m+1}^2 \left(X_{mn} r_o / r_w \right) + J_{m-1} \left(\frac{X_{mn} r_o}{r_w} \right) \right]}}{\left[G - \frac{B_\perp^2 \omega_c \, dG}{2 K_z V_z dX} \right]} (AMP) \quad (13)$$

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

And

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

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.

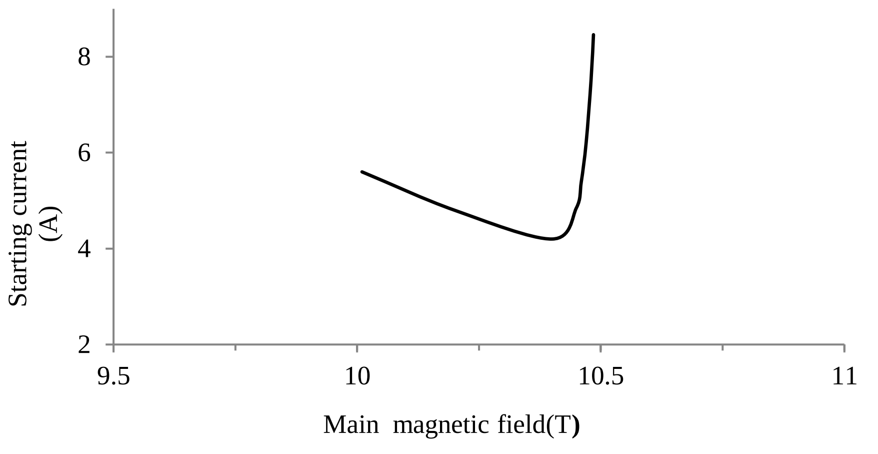

Figure 4. Start oscillation current of cavity $TE_{31,8}$.

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 $_{mnl}$-mode of interest.

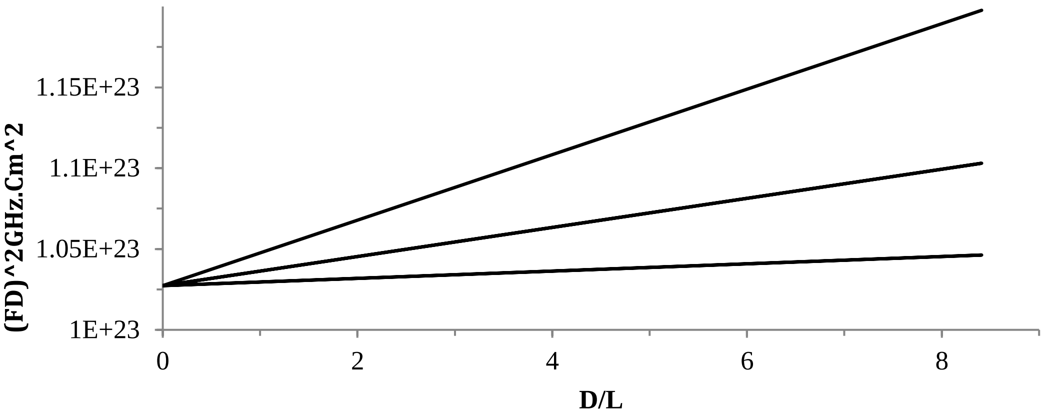

Figure 5. The $TE_{31,8}$ modes in circular cylinder.

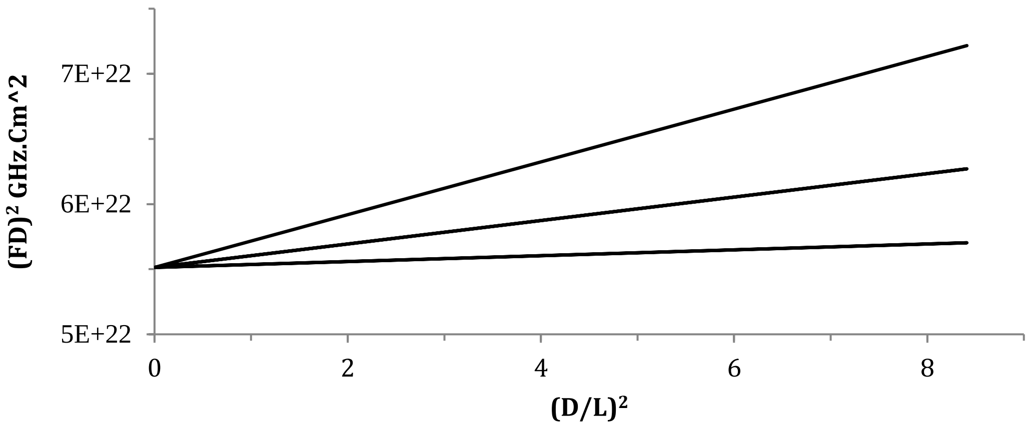

Figure 6. $TE_{8,5}$ - modes in circular cylinder.

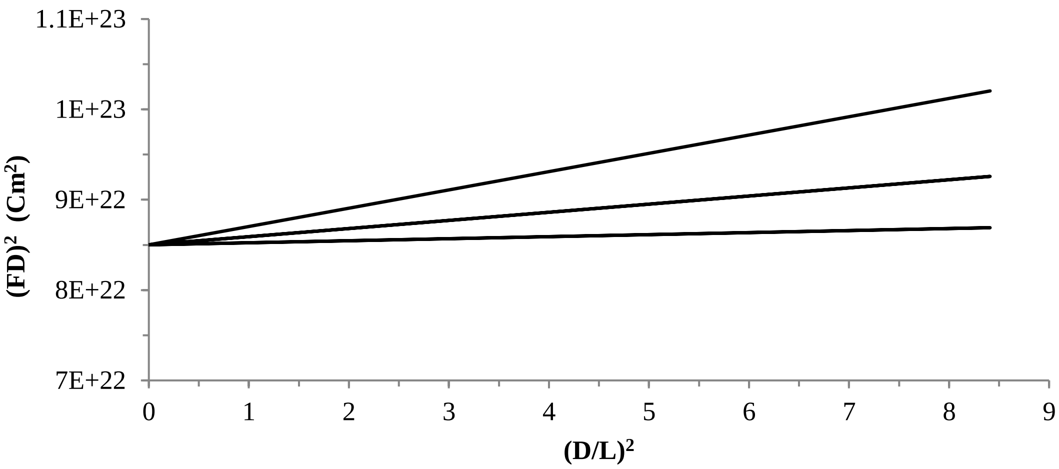

Figure 7. $TE_{10,6}$-modes in circular cylinder.

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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