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Numerical Simulation of the Efficiency of 50 GHz Gyrotron Microwave Tube

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Abstract

This paper presents a simulation study to evaluate the efficiency of a 50 GHz microwave tube operating in the TE_{411} (high- order mode) using computer programming techniques. A simulation program was developed using FORTRAN language to design a single open- cavity gyrotron and investigate the interaction between the electron beam and electromagnetic waves inside the cavity. The program calculates key parameters such as the initial electron guiding center position and the Lamar radius.

The input parameters include the energy of electron, the ratio of velocity, normalized length of cavity, normalized external magnetic field strength and the mode indices (m, n, l), as well as the zero root of the Bessel function $J'_m=0$. the study models an open cavity structure, with an annular mono energetic electron beam exhibiting constant oscillation amplitude. The electron beam is injected into the cavity and propagates under the influence of an external magnetic field.

Keywords: gyrotron efficiency, high power device, microwave amplification.

Introduction:

High- power microwave sources have become important technologies in many scientific and engineering applications, including plasma systems, nuclear fusion research, communication systems, and industrial applications [Thumm M., 2025]. Among these sources, the gyrotron is considered one of the most effective devices for generating high power microwave radiation at high frequencies. It operates based on the interaction between an electron beam and electromagnetic fields inside a resonant cavity. The operating principle of a gyrotron depends on the electron cyclotron resonance phenomenon, where electrons moving under

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the influence of an external magnetic field transfer their kinetic energy to the electromagnetic wave inside the cavity. This interaction results in the amplification and generation of high- frequency microwave power [Sabchevski S.P., 2024]. The performance of the gyrotron is strongly influenced by several parameters, including the cavity geometry, Operating mode, electron beam energy, and magnetic field strength. Achieving high efficiency in gyrotron devices is essential, as it helps minimize the demand for power supplies and lowers the cost of electron cyclotron resonance Heating (*ECRH*). It also reduces ohmic losses with in the cavity, thereby enhancing the operational lifespan of the cavity and decreasing the thermal load on the collector, which simplifies cooling requirements Gyrotrons are specialized microwave sources capable of generating and amplifying high- frequency electromagnetic waves, typically in the range of 0.3 GHz to 300 GHz [Kwo Ray Chu et al., 318, 1980, Adrien Cristian et al. 2018].

This study focuses on a simplified open-cavity design that employs an annular monoenergetic electron beam exhibiting a steady amplitude oscillation mode. The beam of electron is injected from the gun into the interaction cavity and guided by astatic external magnetic field B_0. The electrons travel in an annular path with a fixed guiding center radius R_g. Space charge effects and field mission are assumed to be negligible. High- order modes, such as the TE_{411}- MODE, are important in high-frequency gyrotron designs because they allow operation at higher frequencies while maintaining suitable cavity dimensions. However, the interaction between the electron beam and electromagnetic fields in these modes requires detailed numerical analysis to understand electron motion and optimize the operating conditions. The main problem addressed in this study is the need to investigate the effect of different operating parameters on the efficiency of a 50GHZ.Gyrotron operating in the TE_{411}-MODE and to analyze the electron beam dynamics and its interaction with the electromagnetic field inside the resonant cavity [Savilov,A.,&Shchegollkov,D.2023] This research a mis to develop a numerical simulation model using the FORTRAN programming language to study the performance of single open-cavity gyrotron. The model is used to calculated important parameters such as the initial electron

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guiding center position and the larmor radius, and to investigate the influence of electron beam parameters and external magnetic field on the electron –wave interaction prosses. This study contributes to a better understanding of gyrotron operation and provides useful information for improving the design and efficiency of high-frequency microwave devices.

The analysis considers only axisymmetric transverse electric (TE) modes. Under these assumptions, the relativistic motion of the electrons is governed by a combined electric and magnetic field, as described by the following equation symmetric TE – modes are exited. Under these circumstances, the relativistic electron equation of motion is a combined electric field E and magnetic field B is [R. F. O'Connel 2018].

$$\frac{\partial}{\partial t}[m\gamma_{ral}v(r,\emptyset,z,t)] = -e\left[E_{(r,\emptyset,z,t)} + v_{(r,\emptyset,z,t)} \times B_{(r,\emptyset,z,t)}\right] \cdots\cdots\cdots (1)$$

Where $v_{(r,\emptyset,z,t)}$ is the velocity of electron, e and m are the charge of electron and relativistic mass respectively. $m = \gamma_{ral}m_o$, m_o is the mass of the electrons in the rest state, while γ is the relativistic factor:

$$\gamma_{ral} = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}} \cdots\cdots\cdots (2)$$

Where c is lights speed.

In electron cyclotron maser (ECM) tubes, the electron beam travels from electron gun in to a region subjected to a strong axially symmetric static magnetic field intensity usually increased along the beam propagation direction. Flux densities on the order of several tesla are generally required for proper operation. The magnetic field (B_0) causes the electrons to gyrate in small orbits with a radius equal to Larmor radius, resulting in beam emission at the cyclotron frequency [Kwo Ray Chu et al. 318, 1980, R. F. O'Connel 2018, Santanu Karmaker and Jagadish C. Mudiganti 2021]. The oscillation of electrons in two static field magnetic and electric with varying velocity, the radiate Doppler-shifted waves whose frequencies are close to harmonics of the electron oscillation frequency. This behavior can be described by: [Ioannis Gr. Pagonakis, Alexander B. Barnes 2025].

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$$\omega - k_z v_z = S\Omega \cdots\cdots\cdots (3)$$

Here $k_z v_z$ represents the Doppler shift and s is the resonant harmonic number. That defines the frequency of the emitted waves can be either fast (i.e. $v_{ph} = \frac{w}{k_z} > c$) .

Analytic Solution:

In analyzing the wave propagating inside wave guide along the z-axis. The conducting of walls is assumed to be perfect (with infinite conductivity), while that interior is filled with air considered as a lossless medium (σ =0) the material properties of the medium are characterized by the permittivity εo and the permeability μ_o. By applying the separation of variables technique, the Helmholtz wave equation inside wave guide [Ioannis Gr. Pagonakis and Alexander B. Barnes 2025, Thumm M.2004], the following relations are obtained:

$\nabla_T^2 E_z + K_C^2 E_z = 0 \quad \cdots\cdots\cdots (4)$

$\nabla_T^2 H_z + K_C^2 H_z = 0 \quad \cdots\cdots\cdots (5)$

Here, $\nabla^2{}_T$ represents the two - dimensional Laplace Operator:

$$\nabla_T^2 = \nabla_T \cdot \nabla_T = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \cdots\cdots\cdots (5-1)$$

The parameter k_c denotes the cutoff wave number and is expressed as:

$$kc = 2\frac{2\pi}{\lambda_c} \cdots\cdots\cdots (5-2)$$

Accordingly, the governing equations take the form:

$(\nabla_T^2 + k_c^2) E_Z = 0 \cdots\cdots\cdots (6)$

$(\nabla_T^2 + k_c^2) H_Z = 0 \cdots \cdots \cdots (7)$

The transvers field components can then be written as:

$$E_X = -jB K_{2c} \left(\frac{\partial E_Z}{\partial x} + \eta T_E \frac{\partial Hz}{\partial y}\right) \cdots \cdots \cdots (8)$$

$$E_y = -jB K_{2c} \left(\frac{\partial Ez}{\partial y} - \eta T_E \frac{\partial Hz}{\partial x}\right) \cdots \cdots \cdots (9)$$

$$H_x = -jB K_{2c} \left(\frac{\partial H_z}{\partial x} - \eta T_M \frac{\partial E_Z}{\partial y}\right) \cdots \cdots \cdots (10)$$

$$H_y = \text{- j B } K_{2c} \left(\frac{\partial H_z}{\partial y} - \eta T_M \frac{\partial E_Z}{\partial X}\right) \cdots \cdots \cdots (11)$$

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We obtain Bessel's differential equation whose solution involves the Bessel function $J_m(k_c r)$ by applying the method of variable separation to the wave equation in a cylindrical waveguide. For a circular guide, the longitudinal field components E_z and H_z can be written as: [Ioannis Gr. Pagonakis and Alexander B. Barnes 2025]

$$H_z = c_{\grave{m}} J_m(k_c r)\ \sin(m\phi) \quad \cdots\cdots\cdots (12)$$

$$E_z = c_m J_m(k_c r)\ \cos(m\phi) \quad \cdots\cdots\cdots (13)$$

Here c_m and $c_{\grave{m}}$ denote the coefficients of the longitudinal fields r is the radial coordinate, and $J_m(k_c r)$ represents the Bessel function of the first kind and m By Substituting these forms into Maxwells equations the transverse components in terms of E_z and H_z in circular waveguide [Ioannis Gr. Pagonakis, Alexander B. Barnes 2025].

$$E_{\emptyset} = \frac{1}{k_c}\left[\frac{jmk_z}{r} c_m J_m(k_c r)\sin(m\emptyset) + j\omega\mu k_c' J_m'(k_c r)\cos(m\emptyset)\right] \quad \cdots\cdots\cdots (14)$$

$$H_{\emptyset} = \frac{1}{k_c}\left[\frac{jmk_z}{r} c_m' J_m(k_c r)\cos(m\emptyset) + j\omega\varepsilon k_c J_m'(k_c r)\cos(m\emptyset)\right] \quad \cdots\cdots\cdots (15)$$

Where K_c is the cutoff wave number, K_z is the propagation constant and ω is the angular frequency. The general field distribution in the guide can thus be expressed as:

$$E(r, \emptyset, z) = E(r, \emptyset) exp[i(\omega t - k_Z)] \quad \cdots\cdots\cdots (16)$$

The normalized perpendicular velocity time, relativistic is:

$$\overline{U_\perp} = \sqrt{(\overline{U_\theta} + \overline{U_r})} \cdots\cdots\cdots (17)$$

Let $\wedge$ is the angle between $\overline{U_\perp}$ and $\overline{U_r}$,, hence

$$\overline{U_r} = \overline{U_\perp}\cos(\Lambda) \cdots\cdots\cdots (18)$$

$$\overline{U_\theta} = \overline{U_\perp}\sin(\Lambda) \cdots\cdots\cdots (19)$$

From Equation (18), (19) and one obtains:

$$\frac{\overline{dU_\perp}}{d\bar{t}} = -(E_r\cos(\wedge) + \bar{E}_\theta \sin(\wedge)) + (B_\theta \sin\wedge)\frac{\bar{U}_z}{\gamma_{rai}} \quad \cdots\cdots\cdots (20a)$$

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$$\frac{d\wedge}{d\bar{t}} = \frac{-\bar{U}_{\perp}\sin(\wedge)}{\gamma_{ral}\bar{r}} + \frac{(\bar{E}_r \sin\wedge) - \bar{E}_{\theta}\cos(\wedge)}{\bar{U}_{\perp}} - \frac{\bar{U}_Z(\bar{B}_{\theta})\sin(\wedge) + \bar{B}_r(\sin(\wedge))_z}{\gamma_{rai}\bar{U}_{\perp}} \cdots\cdots\cdots (20b)$$

$$\frac{d\bar{U}_z}{dt} = -(\bar{E}_r + \bar{U}_{\perp}(\bar{B}_{\theta}\cos\wedge) - B_r\sin\wedge) \cdots\cdots\cdots (20c)$$

Equation (20) represents the electron components. If the radiation wave is a summed to propagate in the positive (z)-direction, the Doppler-shifted electron angular frequency (or gyro-frequency) of the propagating wave is defined as [Thumm M. 2004].

$$\Omega_D = K_z V_z + \frac{\Omega_e}{\gamma_{ral}} \cdots\cdots\cdots (21)$$

Where $k_z v_z$ is Doppler shifted frequency, k_z = Axial wave number, v_z= the drift velocity of the electron axis. $\Omega_e = \frac{eB_0}{m}$ is non-relativistic gyro-frequency of the electron, where B_0 Represent external magnetic field flux

$$\frac{d\bar{U}_r}{dt} = \frac{\bar{U}_{\theta}^2}{\gamma_{ral}\bar{r}} - \bar{E}_r - \frac{(\bar{U}_{\theta}\bar{B}_z - \bar{U}_z\bar{B}_{\theta})}{\gamma_{ral}} \cdots\cdots\cdots (22)$$

$$\frac{d\bar{U}_{\theta}}{dt} = \frac{\bar{U}_{\theta}\bar{U}_r}{\gamma_{ral}\bar{r}} - \bar{E}_{\theta} - \frac{(\bar{U}_z\bar{B}_r - \bar{U}_r\bar{B}_z)}{\gamma_{ral}} \cdots\cdots\cdots (23)$$

$$\frac{d\bar{U}_z}{dt} = -\bar{E}_r \frac{(\bar{U}_r\bar{B}_{\theta} - \bar{U}_{\theta}\bar{B}_r)}{\gamma_{ral}} \cdots\cdots\cdots (24)$$

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Results and Discussion:

Determined the gyrotron's efficiency by the relative energy loss by the electrons. The gyrotron efficiency is so called transverse (orbital) efficiency [Oleskandr V. et al. 2002]. The program computes the electron position in (r,ϕ,z) at each time step and its energy, velocity components equation (20) and efficiency (27). Finally, in the cavity energy stored in the wave (W) was evaluated using equation (28). The excitation mode in 50 GHz gyrotron is TE_{411} with value m >3 and l at the lowest value l=1 will be fixed to get high efficiency and the highest cavity quality factor Q, and hence the lowest threshold beam power compared with the $l \neq 1$ modes .Thus if one operates near the threshold of the l=1 mode, the high number l modes will not be excited[Kwo Ray Chu.etal.1980] , it reduces the Ohmic heating losses in the cavity. We used Eqs. (25 and 26) to calculate the operation frequency, the value of operation [Thumm M. 2004].

$$\omega = \mathrm{C}\frac{x_{mn}}{R_0} \cdots\cdots\cdots (25)$$

$$f = \frac{1}{2\pi}\frac{x_{mn}}{R_0} = 49.78\, GHz \cdots\cdots\cdots (26)$$

Frequency to operate with TE_{411} is (49.78 GHz) ~ 50GHz. Finally, the calculated design parameters of 50GHz Gyrotron device with constant external magnetic field are represented in Table (1) and Table (2).

Table (1): Roots of Bessel for high order TE-mode

TE_{mn}-mode	$X_{mn\ell}$
41ℓ	5.318
51ℓ	6.415
61ℓ	7.501
71ℓ	8.578
81ℓ	9.648

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Table (2): Design parameters of a 50 GHz Gyrotron tube.

Mode	TE_{411}
Frequency	50
Cavity length	3.06cm
Beam guiding center position	0.357cm
Cavity radius	0.51cm
Microwave Power	389.66 kW
Cut frequency	2.8886
Beam Voltage	113 kV
Beam current	3.448
Alpha($\propto$=v⊥/‖)	2.5
Operating mode	TE411
Cavity magnetic Field	2.095 Tesla
Efficiency	37.283%
Starting current	2.830 Amp.
X_{mnl}	5.318

The total efficiency can be expressed as [Oleskandr V. et al. 2002]

$$\eta_T = \left(1 - \frac{Q}{Q_{Ohm}}\right) \frac{B_\perp^2}{2\left(1 - \frac{1}{\gamma}\right)} \eta_\perp \cdots\cdots\cdots (27)$$

Where the factor $(\frac{\beta_\perp^2}{2(1-\gamma^{-1})})$ describes the ratio of the initial rotational energy to the initial kinetic energy [Milissa K. 2001]. According to the Refs. [Wong S. K. et al. 1999, Roland Ngegang, 2005 and Sparangle P., Robert A. Smith, 1979], the numerical evaluation of beam efficiency, based on the beam energy after passing through the cavity, is given by:

$$\eta = \frac{\gamma - \frac{1}{N}}{\gamma - 1} \sum_{i=1} \gamma_i \cdots\cdots\cdots (28)$$

Where i stands for 1,2,3……, γ_i is the relativistic factor of i electron and the summation extended overall electrons in the ensemble(here $N = 18$) $\gamma_{ral} = \left(1 - \frac{v_\perp^2 + v_{//}^2}{c^2}\right)^{-\frac{1}{2}}$ is the relativistic factor, $v_\perp$ is azimuthally component of the electron drift velocity , $v_{//}$ is axial component of the electron drift

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velocity, the instantaneous value of the Ω_D can be expressed as[Thumm M. 2004]:

$$\Omega_D = k_z v_{\parallel} + \frac{\Omega_e}{\gamma_{ral}} \cdots\cdots\cdots (29) \quad \text{at} \quad t=0$$

$$k_c = \frac{x_{mn}}{R_0} = K_{\perp} \cdots\cdots\cdots (30)$$

Where X_{mn} is the nth-non van shining root of $\dot{J}(x) = 0$. Hence, the RF-field components of the TE_{mnl} -modes, using the laboratory frame of references, are:

$$P_w = \frac{0.25\varepsilon_0}{Q} L\omega R_0^2 E_0^2 \langle 1 - m^2 | x_{mn} \rangle J_m^2(x_{mn}) \cdots\cdots\cdots (31)$$

$$W = \frac{\varepsilon\pi L E_0^{+2} R_0^2}{4} \left[1 - \left(\frac{m}{X_{mn}}\right)^2\right] J_m^2(X_{mn}) \cdots\cdots\cdots (32)$$

$$P_{\omega} = \frac{\omega W}{Q} \cdots\cdots\cdots (33)$$

$$P_{\omega} = \frac{0.25\varepsilon_0}{Q} L E_0^2 R_0^2 \omega \left(1 - \frac{m^2}{x_{mn}}\right) J_m^2(x_{mn}) \cdots\cdots\cdots (34)$$

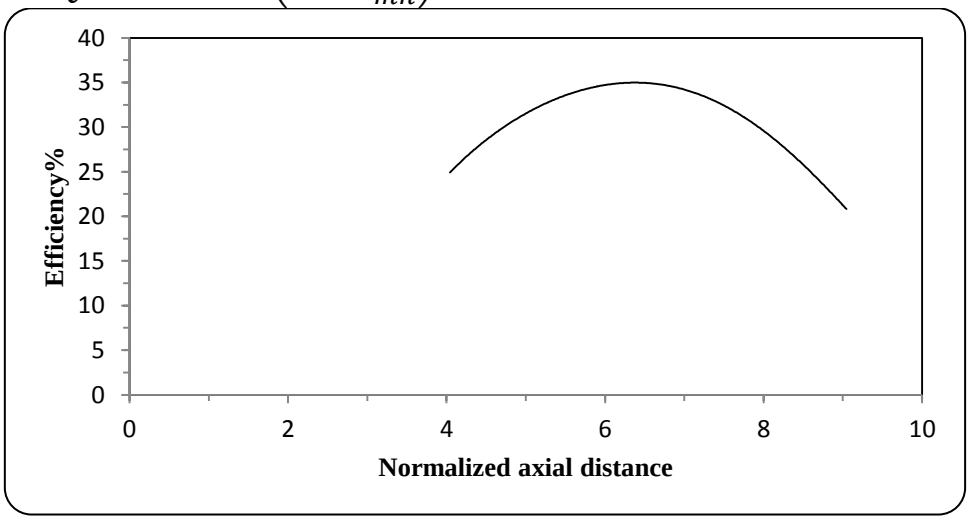

Fig. 1: Efficiency versus length of cavity for mode TE_{411}

Fig. 1 shows the variation of efficiency with normalized axial distance for TE_{411} mode lets break down and discuss its significance in the context of gyrotron tube operation. The shape of the curve represents the beam – wave interaction strength along the cavity at low distance less than the

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interaction is weak, leading to low RF power output. Optimal interaction region (6-7) strong coupling between the electron beam and the RF-field results in maximum energy transfer, i.e., peak efficiency. Beyond optimal point larger of 7 saturation or phase mismatch effects may reduce the interaction, this curve is crucial for cavity length optimization Figures 1. It is clear that good agreement between the reported parameters [Ioannis Gr. Pagonakis, Alexander B. Barnes 2025] and the present calculation are achieved.

Where the cavity radius R_0=0.51, and X_{mnl}=5.318 is the root of Bessel function for TE_{411}-mode.The external magnetic field is one of the important parameters affecting gyrotron operation. It can be adjusted to achieve the optimum operating condition. As shown in Fig.2,the optimum value of the magnetic field was found to be (6.25).The results indicate that the efficiency is highly sensitive to variations in the external magnetic field. The efficiency has been plotted as a function of Z for different values of cavity length as shown in Fig. 3. The rising part has the same slope tendency for six value of cavity length, but with decreasing the cavity length, this cure shifted towards lower values of Z. This suggests that the azimuthally bunching of the electrons may occur at positions located at less values of Z corresponding to the azimuthally electric field component of the RF wave.

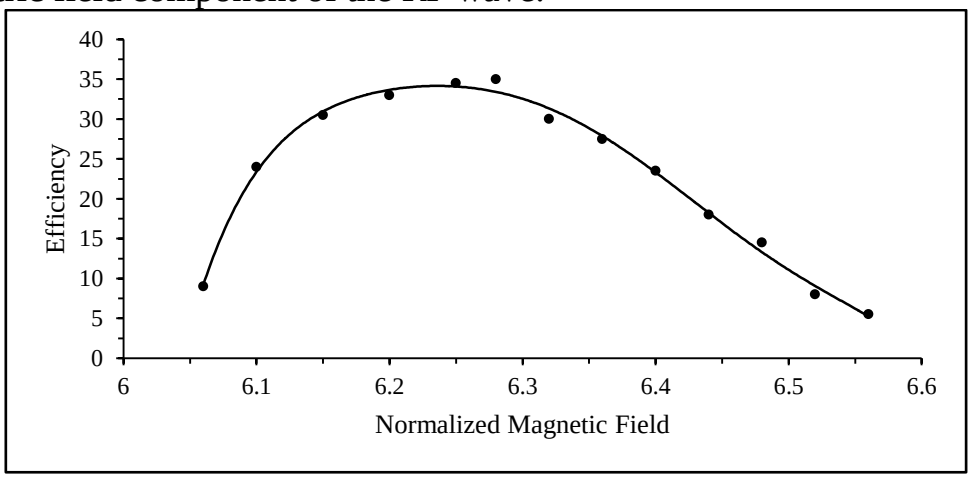

Fig. 2: Efficiency versus external normalized magnetic field for TE_{411} mode.

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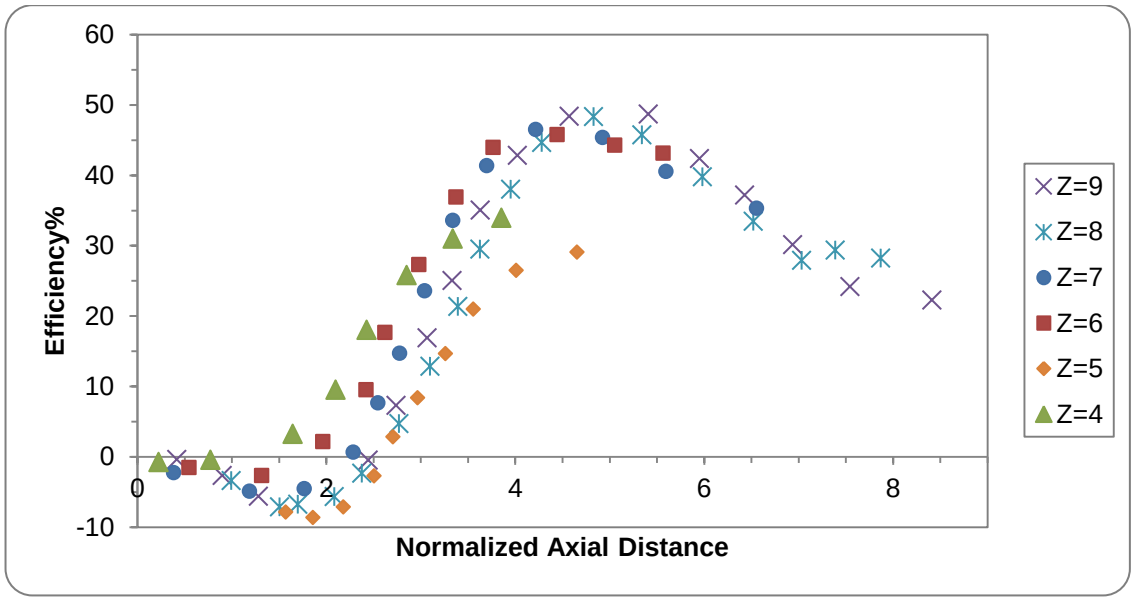

Fig. 3: Efficiency versus normalized axial distance for various cavity.

Analysis of Fig. 3 is demonstrated in Fig. 1 which indicates that the optimum cavity length is $6R_o$. This means that the efficiency is at its optimum value when the electron bunching is saturated and for length greater than $6R_o$ the electrons start to intern the debauching region and the efficiency decreased as shown in Fig1. Where the cavity radius $R_0 = 0.51$, and $X_{mn} = 5.318$ is the *Pth* root of Bessel function for the TE_{411} mode [La Agusu, Idehara T.et al,2005]. The E_θ^2 of the TE_{411} has been plotted versus *R* for all values of *R (R=0 to +R and R=0 to –R*) and for these values Z (i.e. $2.5R_0$, and $4.5R_0$) as shown in figure(4). In this figure the length of the cavity was suggested to be $6R_0$, the beam radius have been suggested to be at the peak of the azimuthal electric field component for TE_{411} mode $R_g = 0.75R_0$ as shown in Fig.(4)

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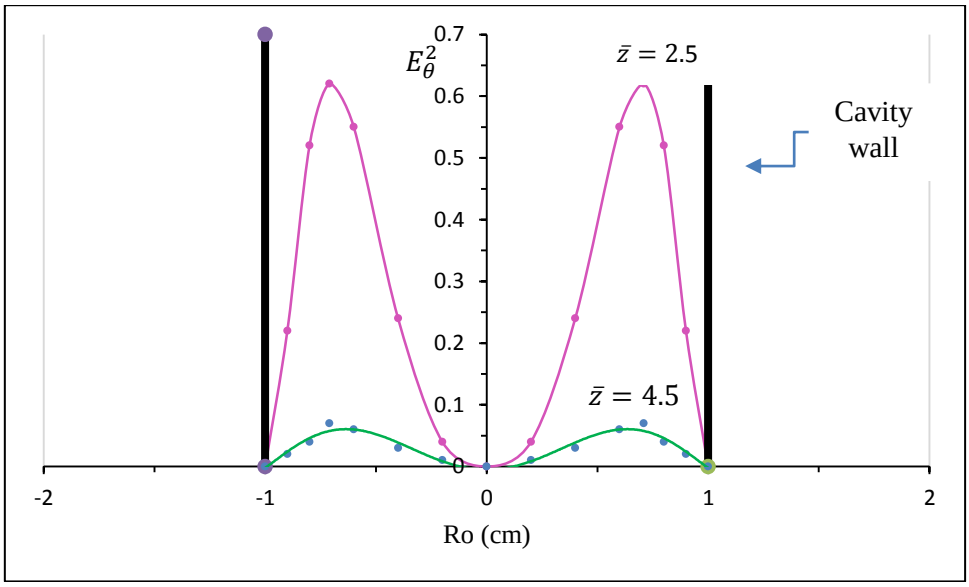

Fig.(4): The electric field component (E_θ^2) versus the radius of cavity (R_o) for TE_{411} mode.

The obtained results were compared with the previous study that investigated the efficiency of a gyrotron operating in the TE_{411}-Mode at a higher frequency shows good agreement with reported [Kwo Ray Chu.1980] Although the previous work was performed at a higher operating frequency, the behavior of the TE_{411}- MODE and the efficiency characteristics follow a similar trend.

Conclusion:

In this research, the design and analysis of a gyrotron tube operating at electric mode TE_{411} -MODE at 50 GHz has demonstrated consistent performance with effective beam-wave interaction and the applied magnetic field on the tube's overall efficiency and operational performance. Cavity length is essential for achieving maximum interaction efficiency. Exceeding this optimal length triggers the phase overly short cavity restricts the required interaction time between the electron beam and the electromagnetic waves. The results confirmed that the gyrotron efficiency is highly sensitive to the external magnetic field tuning, which must be precisely adjusted around the cyclotron resonance value. Any slight deviation from this optimal value leads to a sharp decline in efficiency and output power. The selected TE411-MODE

exhibited robust stability at the targeted 50 GHz frequency, making it promising candidate for applications requiring high-power millimeter-wave sources. In conclusion, this study provides valuable design insights for gyrotron tubes operating in the millimeter-wave spectrum. By optimizing the beam-to-cavity radius ratio and magnetic field parameter, energy conversion efficiency was significantly improved while mode competition was reduced. These findings prove that the TE411 mode is suitable for high-power applications like plasma heating and advanced radar, and further research is necessary to refine cavity design and beam control.

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محاكاة عددية لكفاءة انبوبة جايروترون المايكروويف ذي التردد 50 GHz

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مستخلص البحث:
يقدم البحث الحالي دراسة محاكاة لتقييم كفاءة انبوب جايروترون المايكروويف بتردد 50 كيكا هرتز يعمل في الوضع عالي الرتبة TE_{411} بإستخدام تقنيات برمجة الحاسوب. تم تطوير برنامج محاكاة بلغة الفورتران لتصميم جايروترون ذي تجويف مفتوح أحادي و دراسة التفاعل بين حزمة الألكترونات و الموجات الكهرومغناطيسية داخل التجويف. يحسب البرنامج المعلمات الرئيسة مثل موضع مركز توجيه الألكترونات الأولي و نصف قطر لامار. تشمل معلمات الادخال طاقة الالكترون ومعدل السرعة والطول المعياري للتجويف و شدة المجال المغناطيسي الخارجي المعياري و مؤشرات الوضع (m, n, l) بالإضافة الى جذور معادلة بزل. ينمذج البحث الحالي بنية تجويف مفتوح مع حزمة ألكترونية حلقية أحادية الطور تُظهر سعة تذبذب ثابتة. يتم توجيه حزمة الألكترونات الى التجويف و تنتشر تحت تأثير مجال مغناطيسي خارجي.

الكلمات المفتاحية: كفاءة الجيروترون، جهاز عالي القدرة، تضخيم الميكروويف.