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Analysis and Design of 460 GHz Microwave Gyrotron Oscillator

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K E Y W O R D S

Gyrotron, microwave tubes, millimeter-wave source, high-frequency device.

A B S T R A C T

This paper is concerned with the analysis and design of a gyrotron oscillator with 460 GHz that can excite both modes (TE231) the fundamental (230GHz) and (TE061, TE261) second harmonic (near 460GHz). The oscillator is operated with 12KV beam voltage and 100mA beam current, and a computer program was developed to study the cavity in this oscillator and the wave-particle interaction inside it using the forward finite difference technique as a numerical method. The input data of the program are electron energy, velocity ratio, normalized cavity length, the normalized value of the external magnetic field, the mode number (m,n,l), and nth-non van shining root of J_m^' (x)=0 to calculate the beam and starting currents, frequency and quality factor of the cavity. The results show good agreement with other reported works [10]- [12]-[13]- [14], [15] .This oscillator can serve as a millimeter-wave source at the magnetic field of (16.4T) for enhanced nuclear magnetic resonance and can be used to perform the biological experiment.

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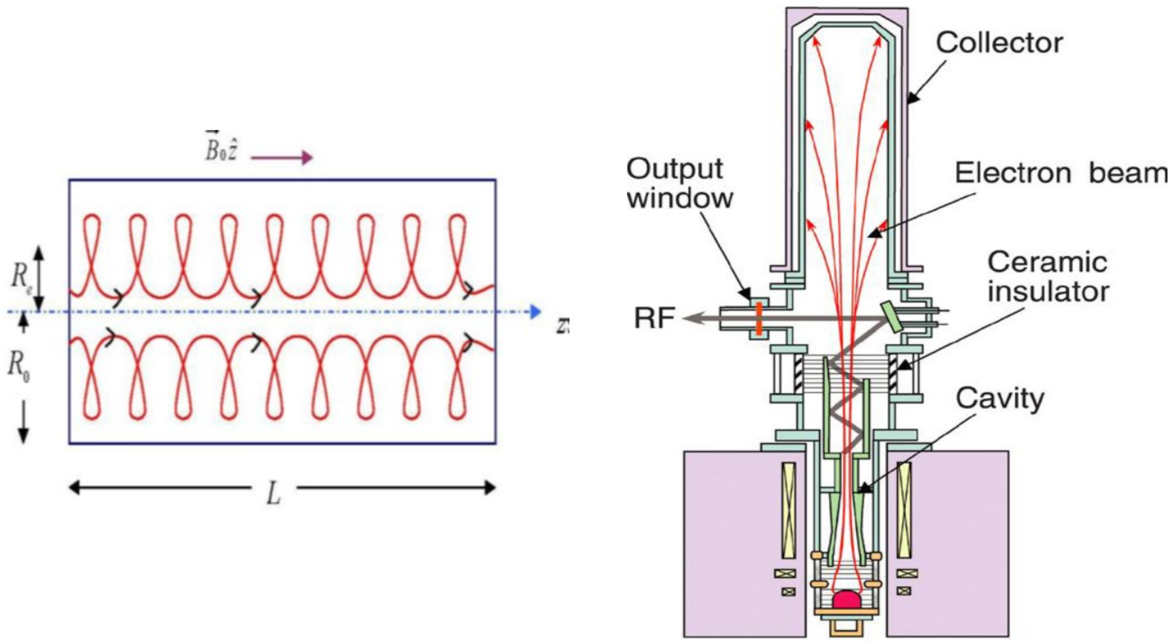
1. Introduction

The electromagnetic spectrum between (300-3000GHz), is interested in Radar applications in Communications, and spectroscopy [1]-[2],[3]. At frequencies (100-170GHz) plasma heating for fusion application. The region of interaction with the electron beam in microwave devices necessarily scales with the wavelength, the increasing frequency of these devices utility above 140GHz. The operating wavelength is smaller than the physical dimensions of the resonator [4]. The highest frequency is 889GHz at Fukui University in Japan [5]. The second harmonic operation of a soviet gyrotron frequency is 326GHz with a power of 1.5 kW [6]. To elevated ohm losses depending on the fundamental interaction to get high efficiency. To operation at higher harmonics interaction needs a large magnetic field. It requires a stronger field for efficient interaction between the beam and the wave. It suffers from the additional complication of mode competition . Efficient interaction between the beam and the wave takes place when the distance between the beam and the surface of the wave guide or cavity structure is smaller than the wave length, this gives rise to increase power loss due to wall heating, which leads to decrease of output microwave power [9]. Furthermore, ohmic loss is a limiting factor in the design of high Q cavities, which is necessary to lower starting current to the operating range of the low power electron gun. In this work when the distance between the beam and the surface of the wave guide or cavity is smaller than the wave length, the power loss increase due to wall heating, which leads to a decrease of output microwave power [7].

2. METHODOLOGY

In this study, a single open-cavity configuration in which an annular mono energetic electron beams sustaining a constant amplitude normal mode of oscillation is considered, the electron emitted by the magnetron injection gun move with a helical path interacting with the wave in the cavity, the electron beam gathers on the collector. The basic schematic of gyrotron is shown in Figure (1.b). The simple cavity of gyrotron operates at 1.5 Mw or below output power. In the gyrotron. In Figure (1.a) the electron beams gyrating with a cyclotron frequency near the operating frequency of the device around and in the magnetic field [8, 9].



(a) (b)

Figure 1: (a) Single cavity of the gyrotron [10], (b) The gyrotron cavity

The beam electrons propagate in an annulus with a constant radius of guiding center (Rg), space charge fields of the beam are neglected i.e no field emission and axial-symmetric $TE-$ modes are exited. Under these circumstances, the relativistic electron Equation of motion is a combined electric field E and the magnetic field B is:

$$\frac{\partial}{\partial t}[mv(r,\emptyset,z,t)] = -e[E_{(r,\emptyset,z,t)} + v_{(r,\emptyset,z,t)} \times B_{(r,\emptyset,z,t)}] \quad (1)$$

Where $v(r,\phi,z,t)$ is th
e electron velocity, *e,* and *m* are the electron charge and relativistic mass respectively. $m = \gamma_{ral} m_o$: m_o is the electron rest mass and γ is the relativistic factor

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

Where c is the speed of light.
The components of Equation (1) in cylindrical coordinates are:

$$\frac{\partial}{\partial t}(mr^{\cdot}) - \frac{m\theta^{\cdot}}{r} = -e(E_r + r\theta^{\cdot}B_z - z^{\cdot}B_\theta) \quad (3a)$$
$$\frac{\partial}{\partial t}(m\theta^{\cdot}) - \frac{r^{\cdot}\theta^{\cdot}}{r} = -e(E_\theta + z^{\cdot}B_r - r^{\cdot}B_z) \quad (3b)$$
$$\frac{\partial}{\partial t}(mz^{\cdot}) = -e(E_z + r^{\cdot}B_\theta - \theta^{\cdot}B_r) \quad (3c)$$

Where the dots indicate differentiation concerning time. Let u=v$\gamma$with components u_r, u_θ and u_z. Equation (3) can be rewritten in the following form:

$$\frac{dU_r}{dt} + \frac{U_\theta^2}{\gamma_{ral}r} = -\frac{e}{m_0}\left(E_r + \frac{U_\theta B_z}{\gamma_{ral}} - \frac{U_z B_\theta}{\gamma_{ral}}\right) \quad (4a)$$
$$\frac{dU_\theta}{dt} + \frac{U_\theta U_r}{\gamma_{ral}r} = -\frac{e}{m_0}\left(E_\theta + \frac{U_z B_r}{\gamma_{ral}} - \frac{U_r B_z}{\gamma_{ral}}\right) \quad (4b)$$
$$\frac{dU_z}{dt} = -\frac{e}{m_0}\left(E_z + \frac{U_r B_\theta}{\gamma_{ral}} - \frac{U_\theta B_r}{\gamma_{ral}}\right) \quad (4c)$$

It is convenient to introduce a normalization scheme by which the cavity radius (R_0) is scaled out of Equation (4). This can be achieved through the following procedure[8] Length normalization to $R_0 = \left(r = \frac{r}{R_0}\right)$, Time normalized to $\frac{R_0}{C}\left(\bar{t} = \frac{tc}{R_0}\right)$ Frequency normalized to), $\frac{c}{R_0}\left(\bar{W} = \frac{wR_0}{C}\right)$Velocity normalized to c $\left(\bar{v}\frac{v}{c}\right)$, Electric field normalized to $\frac{m_0 c}{eR_W}\left(\bar{E} = \frac{EeR_0}{m_0 c^2}\right)$, Magnetic field normalized to $\frac{m_0 c}{eR_W}\left(\bar{E} = \frac{EeR_0}{m_0 c^2}\right)$

$$k_c = \frac{x_{mn}}{R_0} = k_\perp \quad (5)$$

Where xmn is the nth-non van shining root of j(x)=0 Hence, the RF-field components of the TEmn -modes, using the laboratory frame of references, are: Equation (4) may be rewritten in the following form:

$$\frac{d\bar{U}_r}{dt} = \frac{\bar{U}_\theta^2}{\gamma_{ral}\bar{r}} - \bar{E}_r - \frac{(\bar{U}_\vartheta \bar{B}_z - \bar{U}_z \bar{B}_\theta)}{\gamma_{ral}} \quad (6a)$$
$$\frac{d\bar{U}_\theta}{dt} = \frac{\bar{U}_\theta \bar{U}_r}{\gamma_{ral}\bar{r}} - E_\vartheta - \frac{(\bar{U}_z \bar{B}_r - \bar{U}_r \bar{B}_z)}{\gamma_{ral}} \quad (6b)$$
$$\frac{d\bar{U}_z}{dt} = -\bar{E}_r - \frac{(\bar{U}_r \bar{B}_\vartheta - \bar{U}_\theta \bar{B}_r)}{\gamma_{ral}} \quad (6c)$$

The normalized perpendicular velocity-time, relativistic is: $U_\perp = (U_\theta + U_r)^{\frac{1}{2}}$ Let **Λ** is the angle between $\overline{U_\perp}$ and$\overline{U_r}$, hence:

$$U_r = U_\perp \cos(\wedge), U_\theta = U_\perp \sin \wedge \quad (7)$$
$$\frac{dU_\perp}{dt} = -\left(E_r \cos(\wedge) + E_\theta \sin(\wedge) + B_\theta \sin(\wedge)\frac{U_z}{\gamma_{ral}}\right) \quad (8a)$$
$$\frac{d\wedge}{dt} = -\frac{U_\perp \sin\wedge}{\gamma_{ral}r} + \frac{E_r \sin\wedge - E_\theta \cos\wedge}{U_\perp} - \frac{U_z(B_\theta \sin(\wedge) + B_r \sin\wedge)}{\gamma_{ral}U_\perp} \quad (8b)$$
$$\frac{dU_z}{dt} = -(E_r + U_\perp(B_\theta \cos(\wedge)) - B_r \sin(\wedge)) \quad (8c)$$

Equation (8) 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:

$$\Omega_D = k_z v_z + \frac{\Omega_e}{\gamma_{ral}} \quad (9)$$

Where $k_z v_z$ is Doppler term, v_z *is* the axial drift velocity of the electron, $\Omega_e = \frac{eB_0}{m}$ is non-relativistic gyro- frequency of the electron, where B_0 Represent external magnetic field flux density:

$\gamma_{ral} = \left[1 - \frac{v_\perp^2 + v_{/\!/}^2}{C^2}\right]^{\frac{-1}{2}}$ is the relativistic factor, $v_\perp$ is azimuthally component of the electron drift velocity, $v_{/\!/}$ is an axial component of the electron drift velocity, the instantaneous value of the Ω_D can be expressed . The total efficiency of the gyrotron interaction can be written as [9].

$$\eta_\perp = \left(1 - \frac{Q}{Q_{ohm}}\right)\frac{\beta_\perp^2}{2\left(1 - \frac{1}{\gamma}\right)}\eta_\perp \quad (10)$$

3. Results and Discussion

A computer program (Gyro) was constructed to design the cavity and to study the wave-particle interaction inside the cavity. This code uses the forward finite difference technique as a numerical method for solving all governing differential equations (6 and 8) in three dimensions (r,ϕ,z) for each time step in the beam reference frame (BRF). The input data of the program are electron energy, the velocity ratio, normalized cavity length, normalized value of the external magnetic field, the mode number (m,n,l), and nth-non van shining root of $J'_m(x) = 0$. While the program calculates the initial electron guiding center position using Equation (5). It computes at each time step the electron position in (r,ϕ,z) and its energy, and the efficiency from equation(10). From the experimental start, current values of seven observed modes and nonlinear modeling have been performed using the time-dependent simulation code MAGY compared with values calculated in [11], [13].See Fig.4 show the competition of mode in cavity at 460GHz.

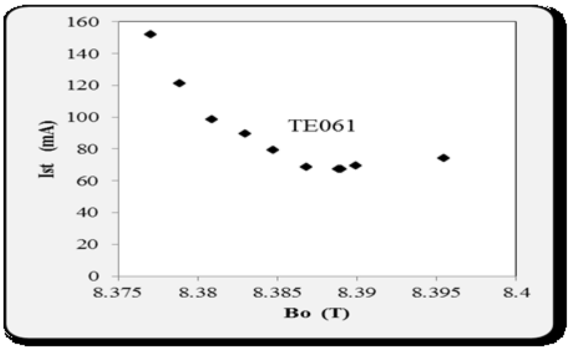


Figure 2: Start oscillation current data versus flux density for second harmonic TE_{061} mode from in the range (8.3T to 8.4T)

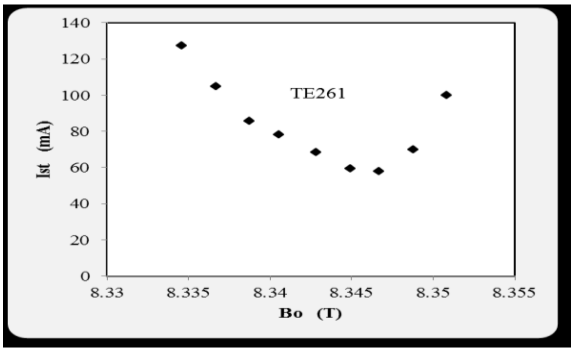


Figure 3: Start oscillation current data versus magnetic flux density for second harmonicTE_{261} mode from (8.33T to 8.355T)

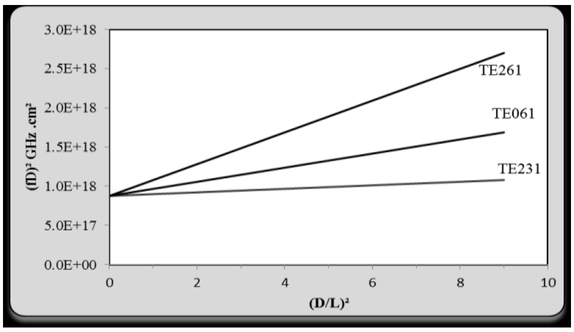


Figure 4: indicates the competing second harmonic ($TE_{061}$and TE_{261}) modes with the dominant mode in gyrotron at 460 GHz.

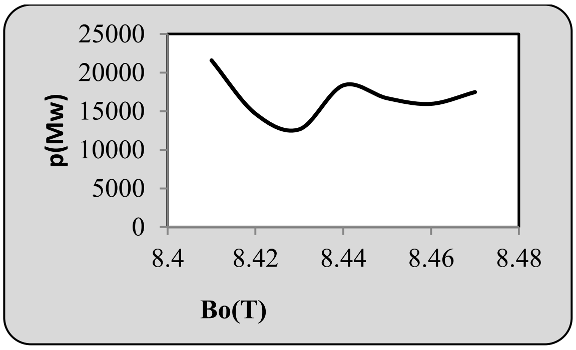


Figure 5: The relation between and magnetic field for the TE_{061}mode

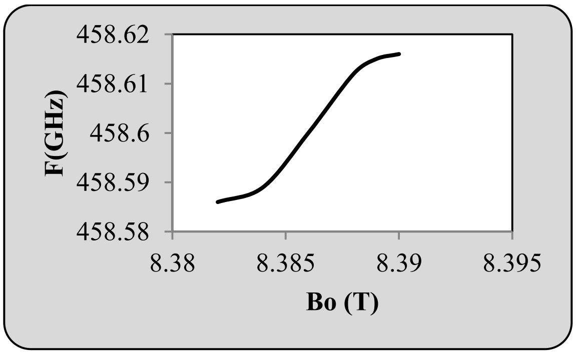


Figure 6: Frequency of the $TE_{0,6}$–mode as a function of mode with the main magnetic field

Figure (4,5) show study the effect of the tapering magnetic

TABLE I: comparisons of the output of the constructed program with those of the reference

TE_{mnl} mode	B_O (T)	I_{St} (mA)	*f* (GHz)	B_O(T) Exp.[10,12]	I_{St} (mA)	*f* (GHz)	B_O(T) Theory [13,14]	*f* (GHz)	I_{st} (mA)
TE_{221}	5.84 8	4	157.06	5.747	4	156.9 0	5.746	156.8 9	4
TE_{421}	8.45	2	217.30	7.933	2	217.1 0	7.926	217.0 9	4
TE_{061}	13.4 0	18	459.14	8.388	67	458.5 6	8.390	456.1 5	67
TE_{231}	8.35 9	18	233.44	8.454	18	233.1 5	8.433	233.1 5	27
TE_{031}	8.62 0	10	238.24 5	8.625	16	237.9 1	8.605	237.9 2	7
TE_{521}	8.59 1	13	246.31 5	8.936	7	246.0 0	8.915	246.0 1	14

TABLE II: comparisons of the outputs of the constructed program with those of the reference [15]

Item	Research result	Ref [15]
Frequency	459.22	460
Magnetic field	8.3899 T	8.4 T
Harmonic number	2	2
Mode	0, 6, 1	0,6,1
Accelerating voltage	12 Kv	12 kV
Beam current	120 Ma	100 mA
Velocity path factor	2	2
Electron beam radius	1.0 mm	1.0 mm
Cavity diffractive Q	31.100	31.100
Cavity ohmic Q	19.400	19.400
Total cavity	12.000	12.000

4. CONCLUSION

The gyrotron (460 GHz) can efficiently produce at the second harmonic in low voltage.12-kV, 100 mA electron beams and the magnetic field applied was 8.7 to study of the harmonic design mode. The minimum starting current of TE-mode is 18mA, agreeing with the linear theory prediction. The gyrotron is currently being processed for cyclotron wave second-harmonic generation at 460 GHz. The values of the starting current vary by changing the applied external magnetic field, and their values are very important for the excitation of modes.

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Appendix1

```
PROGRAM MODE_TE_061
PARAMETER (IMAX=15, JMAX=15)
```

```
COMMON/MES/X(0:IMAX+1,0:JAMX+1)
OPEN (UNIT=2,FILE='XM.DAT')
OPEN (UNIT=6,FILE ='OUT-LT2.OUT')
OPEN (UNIT=8,FILE='OUTAM1.OUT')
OPEN (UNIT=9, FILE='OU1.OUT')
X(0,6)=9.8086
WRITE (6,*)  X(0,6)
DO 1 I=1, 13
READ (2,*) M,N,L,XN,AL,ALPHA,Q
XMN1=X(M,N)
!..........................................................................................................
 CALL α _Factor (XMN1, FMN, BD1, DOL1, IST, PW, η)
!..........................................................................................................
END DO
!
END PROGRAM
```