STUDY OF THE PARASITIC MODES FOR THE 140 GHZ GYROTRON OSCILLATOR

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Abstract

This work reports on the particular gyrotron (140 GHz) and how to improve its operation through the elimination of the parasitic modes which excite with the operating mode (TE_{021}). A computer code which was previously constructed has been used to find and analyze the characteristics of the gyrotron especially the starting current of the mode excitation.

The study involves the parasitic modes of the (140 GHz) gyrotron and the methods of their elimination. Two methods were utilized for this purpose. The first one was the anode voltage variation and the other was the external magnetic field variation. For these two methods all the output characteristics of the gyrotron were analyzed and it was found that the second method is more suitable and gives best results.

دراسة الأنماط الطفيلية لمذبذب جايروترون 140 كيكا هرتز

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الخلاصه

يتضمن البحث الحالى كيفية تحسين عمل جايروترون نوع 140 كيكا هرتز من خلال ازالة الأنماط الطفيلية التى تتهيج مع النمط التشغيلي (TE_{021}) .استخدم برنامج حاسوبى مجهز سابقا لهذا الغرض وذلك لأيجاد وتحليل خواص الجايروترون و تيار البدء لتهيج الأنماط الطفيلية.درس تأثير عاملين لأزالة الأنماط الطفيلية. الأول بتغير جهد الأنود والأخر بتقليل المجال المغناطيسى الخارجى. لوحظ تأثير تغير العاملين على خواص الجايروترون وكيفية ازالة الأنماط الطفيلية . بينت النتائج امكانية الحصول على نتائج أفضل بتغير العامل الثانى بالأضافة الى كونه اكثر ملائمة من تغير العامل الأول .

Introduction

The gyrotron, as all other microwave sources, is based on the conversion of electron–beam energy into radiation using a resonant structure [1]. The conversion takes place in an evacuated metallic cavity and emits in a strong magnetic field (B_o), which causes the electrons to revolve around the field lines at the cyclotron frequency (ω_c) which is given by [2]:

$$w_c = \frac{eB_o}{\gamma_{rel} m_e} \quad \text{………… (1)}$$

Then, consequently, emit Bremsstrahlung radiation as does any electric charge in its accelerated motion. In the equation (1), B_o is the magnitude of the guided magnetic field and the relativistic mass factor (γ_{rel}) defines as [2]:

$$\gamma_{rel} = [1-(v/c)^2]^{-\frac{1}{2}} = 1 + \frac{eV}{m_o c^2} \text{ .... } (2)$$

Where e, m_o and v are the charge, rest mass and velocity of the electrons respectively and (eV) is the electron kinetic energy.

If the electrons radiate independently of each other, the resulting net coherent radiation field is zero because of the superposition of waves in random phase. To include phase correlation between electrons, gyrotrons elegantly utilize the relativistic dependence of the cyclotron frequency (w_c) on the electron energy: the more energetic the electron, the slower it rotates. Assuming that the magnetic field in the cavity has been tuned so that the cyclotron frequency equals the eigen frequency of the operating mode, ($w_c = w$) , the electrons experience in there own frame of reference a constant electric field that either accelerates or decelerates them depending on the relative phase of rotation. The changes in energy immediately imply opposite changes in cyclotron frequency, and eventually all electrons become bunched in the “neutral” phase of the electric field, emitting coherent Bremsstrahlung [3].

In the gyrotron, the electron beam exchanges energy with the radio frequency RF wave when passing through a resonator and operates near the cutoff frequency (w_{co}), that is [2]:

$$w_c \approx w_{co} \text{ ………..…. } (3)$$

Under the same condition (cutoff frequency) $k_\perp >> k_Z$ and the resonant condition equation equation is given by:

$$w/c = k = \left(k_\perp^2 + k_z^2\right)^{\frac{1}{2}} \text{ ………..…..} (4)$$

Reduces to $w/c = k = k_\perp$ where $k_\perp$ and k_z are the transverse and axial wave numbers of the waveguide modes [4]. One of the most important problems in designing any gyrotron is the excitation of the parasitic modes with the operating or designing mode. These modes will compete the original mode and reduce the efficiency of the device. This problem encouraged the authors to think about a study of how to control or to minimize the effect of these parasitic modes. For this purpose, the 140 GHz gyrotron studied by Temkin et al. [5] was selected because it is the most popular one among the resent gyrotrons having a high number of parasitic modes.

The gyrotron is designed at any resonant harmonic number ($s = 1,2,.......$), therefore it may be possible to simultaneously excite a parasitic mode or multimode oscillation. [5].

There are variety reasons why multimode oscillation should be avoided when operating a high-power gyrotron. If the tube is operating in the desired mode and a parasitic mode is accidentally excited, the efficiency will generally decrease. This is due primarily to adverse bunching of the electron beam by the parasitic mode of interest [6].

Cavity Fields

Gyrotron interaction cavities are usually cylindrical, with tapers of various sizes and lengths on either end to aid in mode selection. Such a cavity is capable of supporting a large number of resonant electromagnetic modes, but gyrotrons are typically operated near cutoff frequency $\left(k_\perp \rangle\rangle k_z\right)$, so the Transverse Magnetic TM modes are generally suppressed in favor of TE (Transverse Electric) modes [7].

The cylindrical cavity RF-field components of the TE_{mnl}–modes (*mnl* are mode numbers) derived from Maxwell’s equations are [2]:

$$E_r = -\frac{m}{k_c r} E_o J_m(k_c r)\sin(m\phi - wt)\sin(k_z z) \text{.........} (5)$$

$$E_\phi = -E_o J'_m(k_c r)\cos(m\phi - wt)\sin(k_z z) \text{...} (6)$$

$$E_z = 0 \text{ ….…. } (7)$$

From equ. (7), the axial component of the electric field (E_Z) is zero. This is because of the kind of the mode (transverse electric mode, TE, for which $E_z = 0$) exists within the cavity resonator of the gyrotron. The corresponding magnetic field components of the above three equations are:

$$B_r = \frac{k_z}{w} E_o J'_m(k_c r)\sin(m\phi - wt)\cos(k_z z) \text{ ……….} (8)$$

$$B_\phi = \frac{k_z}{w}\frac{m}{k_c r} E_o J_m(k_c r)\cos(m\phi - wt)\cos(k_z z) \text{ ……..} (9)$$

$$B_z = \frac{k_c}{w} E_o J_m(k_c r)\sin(m\phi - wt)\sin(k_z z) \text{....} (10)$$

Here, r is the cavity radius, $k_c = k_\perp = X_{mn}/r$ is the transverse wave number, X_{mn} is the nth root of J'_m equal to zero, J_m is a Bessel function of the ordinary type, w is the wave angular frequency, $k_z = l\pi/L$ is the axial wave number, and L is the cavity length [2].

The Electron Bunching Mechanism

The annular electron beam in the cavity resonator, and in the absence of any electric field, will orbit the guiding center with angular frequency given by equation (1). If a transverse electric field is present, the electrons will feel an additional electric force (-eE), which will cause some electrons to accelerate and others decelerate depending on the relative phase of electric field [7]. The change of the energy of an electron can be found by taking the scalar product of the Lorenz equation of an electron in an electromagnetic field with $\vec{v}$, i.e.:

$$\frac{d\vec{p}}{dt}\cdot\vec{v} = -e(E+\vec{v}\times\vec{B})\cdot\vec{v} \qquad \text{........}(11)$$

Or

$$\frac{dW}{dt} = -e\vec{E}\cdot\vec{v} \qquad \text{.........}(12)$$

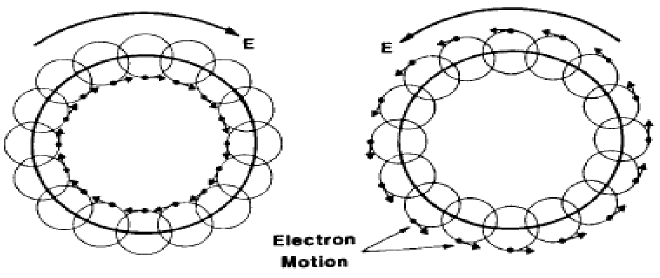
Since $(\vec{v}\times\vec{B}) \perp \vec{v}$, so the second term of equ. (11) vanishes. In the above equations p, W and v are the momentum, energy and the velocity of the electron, respectively.

From equation (12), it's clearly seen that those electrons which have a velocity component in the direction of ($\vec{E}$) are decelerated ($dW / dt \langle 0$),and those with a velocity component opposite to ($\vec{E}$) are accelerated ($dW / dt \rangle 0$).

Since the cyclotron frequency of an electron is inversely proportional to its relativistic mass factor γ_{rel}, see equation (1), those electrons which lost energy are in the direction of electric field, i.e. $\vec{E}.\vec{v} \rangle 0$ and the Larmor radius (r_L) decreases due to $r_L = v_L / w_c$, then the electrons can be gyrated slower while those that gained energy gyrated faster [8].

If the electric field frequency (w) is exactly equal to the electron cyclotron frequency (w_c), this bunching process will continue until the entire beamlet is bunched at a zero-field phase point. In order to extract power, the bunch must be formed at a field maximum; this is accomplished by a slight tuning of the axial magnetic field so that the cyclotron frequency is slightly lower than the RF frequency. When this condition is met, the bunch (electrons) orbits in phase with the electric field and gives up their rotational energy to the field. A diagram of this condition (Figure (1)) shows how the phase of the electric field (E) changes (alters) with the direction of the electrons circulation with the same frequency ($w = w_c$) along the cavity resonator.

The entire electron beam is shown, with the smaller circles representing the Larmor radii of each beamlet. Once a beamlet has become bunched in phase with a cavity mode, it gives up its rotational kinetic energy to the mode, thus increasing the field strength and promoting more bunching [7].



Results and Discussion

1.Introduction

The effects of two parameters were studied. The first one was the variation of the anode or beam voltage (V) within a given limit and the second one is the variation of the external magnetic field (B_o). The effects of these two input parameters on the efficiency of the device were observed.

For this purpose a program written in Fortran 77 language is used. The program, named (GYROTRON 1), was calibrated using some input data of Chu et al. [9]. The computed results are compared to their corresponding measured values of [9] and good agreements were observed.

2.Study of 140 GHz Gyrotron

In this work, the fundamental 140 GHz gyrotron oscillator designed by Temkin and Kreischer [5] is studied. The characteristics of (140) GHz gyrotron operate in TE_{021} mode with its X_{mn} value equals to (7.0151) as given by reference [5] are listed in the Table (1).

Table 1: The characteristics of the 140 GHz gyrotron [5].

Mode	TE_{021}
X_{mn}	7.0151
V	65 kV
Z	7.5
$\overline{R}_e$	0.76
R_o	0.239 cm
$\overline{B}_o$	7.9
$\overline{E}_o$	0.13
α	1.5

Where X_{mn} is the n^{th} nonzero root of J'_m [J_m is the Bessel function of the first kind of order(m)]. The values of the normalized axial distance Z (normalized to the cavity radiusR_o) and the initial normalized electric field $\overline{E}_o$ (normalized tomc^2/eR_o) were not mentioned in the work carried out by ref. [5], so their estimated values are found from the plot of the efficiency with either (Z) and ($\overline{E}_o$) repetitively as shown in figures (2) and (3).

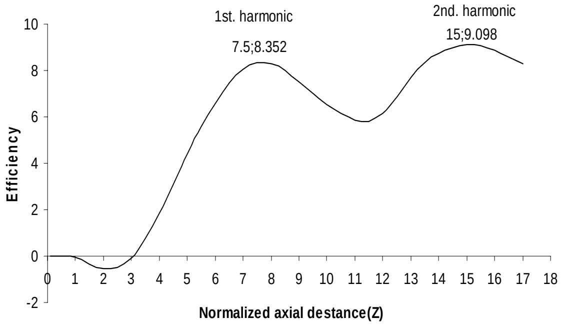


Figure 2: Efficiency versus the normalized axial distance (Z).

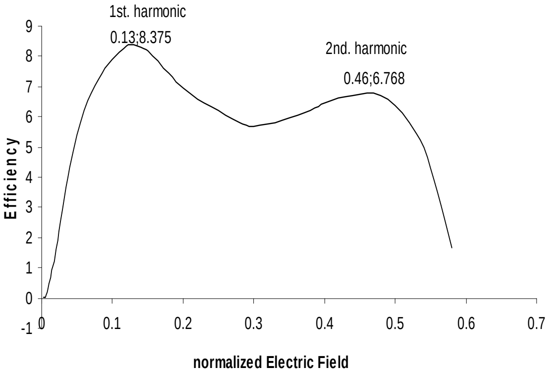


Figure3: Efficiency versus the normalized electric field ($\overline{E}_o$)

$\overline{R}_e$ is the normalized electron beam radius (normalized to cavity radius R_o), $\overline{B}_o$ is normalized magnetic field (normalized to mc/eR_o), and α is the pitch factor (ratio of the normal velocity component to the parallel velocity components of the electrons). From the figures (2) and (3), the value of the (Z) is (7.5) and $\overline{E}_o$ is (0.13) corresponding to the first maximum efficiency must be taken because of the fundamental operation of the studied gyrotron (140 GHz). Table (2) represents the output parameters (characteristics) of 140 GHz gyrotron by using the same program (GYROTRON 1) for the input data of the Table (1).

Table 2: The output parameters of 140 GHz gyrotron.

Frequency (GHz)	140.4
Diffractive quality factor	1459.26
Beam current (A)	1.194
Starting current (A)	0.465
Output Power (kW)	6.501
Net Efficiency (%)	8.375

3.Parasitic Modes Oscillations within the 140 GHz Gyrotron

The parasitic modes define as those modes which may excite along with the operating mode inside the cavity resonator and cause to decrease the efficiency of the gyrotron.

One of the most important problems in the design of the fast –wave devices such as gyrotron oscillator is the excitation of the parasitic modes along with the desired mode. If the cavity of the gyrotron oscillator is large then the density of modes, that can support the cavity, rises and the probability of excitation the parasitic modes increases [10], in the fast-wave devices the electron beam should not localized near the walls, and the cross section of the devices can be much larger than the squared wavelength. This causes greatly to increase the output power, but it also may cause a strong competition between modes having different transverse structure [11], due to the above two reasons the parasitic mode excites and causes to decrease the efficiency which is due to primarily the adverse bunching of the electrons beam and warm the cavity walls [10]. The operating mode of the 140-GHz gyrotron is azimuthally symmetric mode (i.e. $m = 0$) and the parasitic modes which may be excited with this kind of mode are azimuthally asymmetric mode (i.e. $m \neq 0$) [5].

The fundamental and second harmonic parasitic modes which could be excited along with the operating mode of the 140 GHz were found by using the equation:

$$(X_{mn})_{op} = (X_{mn})_1 = (X_{mn})_2 / 2 = 7.0151 \quad ..(13)$$

Where X_{mn} is the n^{th} zero of J'_m, and (op) denotes the operating mode. While, the subscriptions labeled (1) and (2) are denotes the parasitic mode excitation at the fundamental and second harmonic oscillators, respectively.

The starting current for the oscillation of these parasitic modes are found from the outputs of using the program (GYROTRON 1). From ref. [2] and the equation (13), there are three possible parasitic modes at the fundamental harmonic and four parasitic modes at the second harmonic compete the original operating mode as listed in the Table (3) with their X_{mn} and starting currents. All these modes are asymmetric which must be the case as stated before.

Table 3: The competitive parasitic modes with TE_{021}.

Modes	X_{mn}	Harmonic no.(s)	Starting current $I_s(A)$
TE_{511}	6.415	First	- 80.144
TE_{221}	6.705	First	- 0.829
TE_{611}	7.5	First	- 752.6
$TE_{12,1,1}$	13.877	Second	0.218
TE_{531}	13.987	Second	0.054
TE_{821}	14.115	Second	- 0.008
TE_{341}	14.587	Second	7.933

From the Table (3), it is clear that for all the three fundamental parasitic modes ($TE_{511}, TE_{221}, and\, TE_{611}$), because of their negative values of starting current they will not excite along with the operating mode (TE_{021}) of the gyrotron. This means that they will not have any effect on the gyrotron performance.

For the second harmonic parasitic modes, the first two modes ($TE_{12,1,1}$ and TE_{531}) have their starting currents less than the beam current of the operating mode ($I_o = 1.194A$), see Table (2), so they can excite within the cavity and cause the perturbation of the phase distribution of the electrons and decrease the efficiency of the device (gyrotron). The third second harmonic parasitic mode (TE_{821}) which competes the operating mode can not excite, due to the negative value of its staring current, while the fourth one (TE_{341}) will not excite because its starting current value (7.933A) is greater than the beam current of the operating mode. The aim of this work is to eliminate the first two second harmonic parasitic modes ($TE_{12,1,1}$ and TE_{531}) in order to have a perfect design with a single pure operating mode which works more stable with higher efficiency.

4. Operation Improvement through the Beam Voltage Study.

One of the most important input parameters to design a gyrotron is the anode voltage (V) which accelerates the electron beam inside the cavity toward the electron collector. The variation of this parameter was performed from the original designed value (V = 65 kV) of the studied gyrotron up to (V = 74 kV) with a constant designed external magnetic field ($B_o = 5.64\ Tesla$).

The effect of this variation on the efficiency and starting currents of the operating mode (TE_{021}) and the two parasitic modes are tabulated in Table (4). The limits of the beam voltage was selected from (65-74 kV), because from the Table (4), for the beam voltage less than (65 kV) the efficiency (η) found to be decreases with increasing beam current (I_o), which is not the aim of this work, while for values greater than (74 kV) although the efficiency increases but the starting current (I_s) of the operating mode (TE_{021}) becomes more than the beam current (I_o) which will not have sufficient time to excite the cavity operating mode because of its high velocity or energy as they are directly proportional to the anode or beam voltage (V).

Table 4: The starting currents of the operating mode (TE $_{021)}$ and parasitic modes (TE $_{12,1,1}$ and TE $_{531)}$ as a function of the beam voltage at B_0=5.64 T

Beam voltage (kV)	TE $_{021}$			TE $_{12,1,1}$	TE $_{531}$
	(%) η	$I_o(A)$	$I_s(A)$	$I_s(A)$	$I_s(A)$
65	8.375	1.194	0.465	0.218	0.054
66	7.953	1.238	0.384	0.456	0.049
67	10.891	0.89	0.34	-2.99	0.042
68	14.123	0.676	0.31	-0.378	0.044
69	14.574	0.646	0.3	-0.224	0.052
70	16.244	0.571	0.302	-0.178	0.066
71	19.256	0.475	0.308	-0.165	0.092
72	20.423	0.442	0.321	-0.17	0.142
73	21.161	0.42	0.342	-0.19	0.256
74	23.579	0.372	0.371	-0.23	0.582

When the studied gyrotron (140 GHz) operates at its own beam voltage (65 kV), then the starting currents of the operating mode and both parasitic modes are less than the beam current which means that they are all exciting together and giving rise to a low efficiency (8.375) percent.

Increasing the beam voltage to 66 kV, will lead to a slight decrease of the efficiency because of the starting currents of the competing modes which are still active. However, as the beam voltage from 67 kV to 74 kV, the starting currents of the operating mode (TE_{021}) are still less than the corresponding values of the beam current which must be the case in order to excite the operating mode. Moreover, the starting currents of the parasitic mode ($TE_{12,1,1}$) corresponding to each value of the beam voltages were negative which means the disposability of its excitation (i.e., it is eliminated). For second parasitic mode (TE_{531}), its starting currents increase with increasing the beam voltage till it reaches the value of ($I_s = 0.582A$) which is greater than the beam current of the operating mode ($I_o = 0.372A$) which corresponds to the optimum value of beam voltage at 74 kV and in this way it is also eliminated. Due to this variations, the efficiency of the devices become (23.579 %) at the optimum value of beam voltage (74 kV).

The variation of the beam voltage from 65 kV to the new proposed value (74 kV) will also act on the values of the starting currents of the other parasitic modes given in Table (3) (i.e., the fundamental parasitic modes TE_{511}, TE_{221} and TE_{611} and also the second parasitic modes TE_{821} and TE_{341}). Due to the above beam voltage variation the starting currents of these modes become (25.209, -0.26, -219, 10.9 and 74.83), respectively.

From these values, it is clear that none of them will appear as the parasitic mode or they will not excite with the operating mode of the present gyrotron.

Operation Improvement through the Variation of the External Magnetic Field

The second possible parameter which can be varied to study the improvement of the gyrotron design is the external magnetic field (B_o). This parameter has a great influence on the determination of the cyclotron frequency (w_c) and the Larmor radius (r_L) of the electrons and, therefore, acts on the efficiency improvement as well as the beam and starting currents evaluation. Table (5) represents how the variation of the normalized magnetic field acts on the efficiency (η) of the device and also on the beam and starting currents of both operating and the two parasitic modes in the cavity.

Table 5: Efficiency and the starting currents of the operating and parasitic modes as a function of the normalized magnetic field at $V = 65\ kV$.

$\overline{B}_o$	TE $_{021}$			TE $_{12,1,1}$	TE $_{531}$
	(%) η	$I_o(A)$	$I_s(A)$	$I_s(A)$	$I_s(A)$
7.9	8.375	1.194	0.465	0.218	0.054
7.89	7.942	1.259	0.404	0.324	0.046
7.88	8.721	1.146	0.363	0.697	0.043
7.87	11.112	0.9	0.335	-3.984	0.041
7.86	13.537	0.738	0.316	-0.533	0.043
7.85	15.019	0.665	0.307	-0.299	0.046
7.84	14.616	0.684	0.297	-0.219	0.052
7.83	16.032	0.623	0.295	-0.182	0.061
7.82	18.464	0.541	0.296	-0.165	0.075
7.81	20.601	0.485	0.301	-0.159	0.098
7.8	21.181	0.472	0.311	-0.161	0.136
7.79	21.403	0.467	0.324	-0.171	0.206
7.78	23.382	0.427	0.342	-0.191	0.348
7.77	25.547	0.391	0.365	-0.222	0.715

In the Table (5), the range of the normalized magnetic field $\overline{B}_o$ variation started from 7.9 and decreased to 7.77 only. This is because of the values less than 7.77 the starting current of the operating mode becomes more than the beam current which means that below this value the operating mode (TE_{021}) will not excite. Also, for values greater 7.9 the efficiency decreased and reached (6.5%) for ($\overline{B}_o = 7.91$). From the same table, it is clear that the optimum value of the normalized magnetic field is (7.77) less than the designed value (7.9). At this new value, the efficiency is nearly three times the previous value and the starting current of the operating mode (0.365 A) is still less than the new beam current value (0.391 A). This improvement in the design is due to the elimination of the two second harmonic parasitic modes mentioned before ($TE_{12,1,1}$ and TE_{531}) and their excitation with the operating mode with the initial designed normalized magnetic field value ($\overline{B}_o = 7.9$). It should be mentioned that we made a number of runs where we have changed both the beam voltage and magnetic field those given in Tables (4) and (5). In all other cases, except those given in these two tables, the starting current of the operation mode is greater than the beam current. This indicates that for best performance, that is elimination the parasitic modes and obtaining a high efficiency one has to choose either of two sets; ($V = 65kV$) with ($\overline{B}_o$=7.9) or ($V = 74kV$) with ($\overline{B}_o$=7.77).

The parasitic mode (TE_{531}) is eliminated because its starting current became more than the beam current value, while the elimination of the other one ($TE_{12,1,1}$) was ensured from its negative value (- 0.222).

The starting current of the other parasitic modes given in Table (3) also calculated with the new value of the normalized magnetic field (7.77), and the results are presented in Table (6). This table indicates that all of these modes do not have any effects on the operating mode, due to their negative and high values of their starting current.

Table 6: Starting current for five parasitic modes at $\overline{B}_o = 7.77$

Modes	Starting current (A)
TE_{511}	- 93.95
TE_{221}	- 0.249
TE_{611}	184.72
TE_{821}	- 1.303
TE_{341}	23.098

Voltage Depression (ΔV) Investigation

For the continuous wave (CW) gyrotron operation, the beam current should be smaller than the limiting current at least by two factors [12].The limiting current is the current for which the voltage depression becomes so large that the beam can not propagate. In the present work, the voltage depression (ΔV **)** given by [12]:

$$\Delta V \approx 60\Omega \frac{I_o}{\beta_z}.\ln(\frac{R_o}{R_e}) \quad \text{……………..} (14)$$

is calculated for the present gyrotron (140 GHz) before and after changing both the anode voltage and the external magnetic field.

β_z is the normalized axial velocity component of the electrons (normalized to the speed of light). The initial value of ΔV was found to be (66.2 V) using the Table (7). While after increasing the anode voltage from (65 to 74) kV, ΔV became 20.2 V and after decreasing the magnetic field from (5.64 to 5.54) Tesla it was found to be 22.6 V. These two values are less than the initial value of ΔV which means that in using both the methods for the parasitic modes elimination there is no problem in lowering the values of the beam currents and they are still within the permitted limit.

Table 7: Some characteristics of the 140 GHz gyrotron due to the variation of anode voltage and external magnetic field.

Parameters	$V = 65kV$ $B_o = 5.64T$	$V = 74kV$ At $B_o = 5.64T$	$V = 65kV$ At $B_o = 5.54T$
γ_{rel}	1.125	1.115	1.099
α	1.415	1.159	1.142
β_z	0.295	0.301	0.283
$\beta_\perp$	0.417	0.349	0.324
I_o (A)	1.194	0.372	0.391
P_w (kW)	6.501	6.501	6.501

Conclusions

For the present study, the following conclusions are obtained:

1- The two parasitic modes ($TE_{12,1,1}$ and TE_{531}) exciting inside the cavity can be removed by increasing the beam voltage from (65 to 74) kV, resulting the efficiency to increase from 8.374 to 23.579 percent.

2- Reducing the external magnetic field from (5.64 to 5.54 T) will also eliminate the parasitic modes of 140-GHz gyrotron, and the efficiency increases to 25.547 percent.

3- The operation of removing parasitic modes is done by two methods, which are increasing the beam voltage and reducing the external magnetic. However, the computed results show that the second one is better than the first one, because the efficiency improvement using the second method is higher than that of the first one after removing the parasitic modes. Moreover, the starting current is less than the beam current of the desired mode in the case of reducing magnetic field, while in the case of the beam voltage changing method they are very close to each other (starting and beam current). Also, economically, the reduction of the external magnetic field (B_o) is better than increasing the input anode voltage which may also causes breakdown.

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