Mode Selection for a Terahertz Gyrotron Based on a Pulse Magnet System

MODE SELECTION FOR A TERAHERTZ GYROTRON BASED ON A PULSE MAGNET SYSTEM

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Abstract

The $TE_{6,11}$ mode has been selected as a candidate for the second harmonic operation of a terahertz gyrotron at 1007.68 GHz. The predicted efficiency is 8.6 percent for the output power 0.38 kW. Time-dependent, multi-mode calculations have been carried out to investigate stability of a single-mode operation at second harmonic. It has been found that with the beam current 0.111 A and the magnetic field 19.282 T the second harmonic operation in the $TE_{6,11}$ mode is possible.

Keyword: gyrotron, mode selection, second harmonic, mode competition, terahertz.

1. Introduction

A gyrotron is an important source of the short wavelength coherent radiation. High power gyrotrons in the millimeter wave range are developed worldwide for the electron cyclotron heating (ECH) of the plasma in nuclear fusion installations [1,2,3] and for technological applications [4]. In addition, high frequency medium power gyrotrons are of interest for plasma scattering measurements [5,6,7], electron spin resonance (ESR) experiments [8,9], etc. A series of such gyrotrons operating in submillimeter wavelength at second harmonic have been developed at Fukui University (so-called Gyrotron FU Series) [10-15] and at University of Sydney [16].

A gyrotron operating at the second harmonic for a given frequency requires only half of the magnetic field in comparison with a gyrotron operating at fundamental harmonic. In other words, for a given magnetic field the second harmonic operation makes it possible to double the gyrotron frequency. For example, a low-power, CW, frequency tunable gyrotron at University of Sydney was operated at 516 GHz at the second harmonic [16] and the FU IVA gyrotron, the latest in gyrotron FU series, has achieved 889 GHz also at the second harmonic [17].

Generally, second harmonic modes are difficult to be excited because of the mode competition between the fundamental and second harmonic modes [17-20]. Due to mode competition, high-power operation at fundamental may suppress the second harmonic mode, making the second harmonic operation of a gyrotron impossible. This phenomenon has been intensively studied experimentally (see, e.g., [19]) and then theoretical analysis follow the experimental results [20, 21]. Various approaches have been proposed to eliminate undesirable mode competition, e.g. by special design of cavities and careful choice of gyrotron operating parameters [11].

A terahertz gyrotron based on a pulse magnet system has been developed in the Research Center for Development of Far-Infrared Center, Fukui University (FIR FU). This gyrotron is a modification of the gyrotron FU III with the 12 T superconducting magnet [12,13]. In order to reach frequencies of the order of one terahertz, a magnetic field of about 38.6 T is needed for the fundamental and of about 19.3 T for the second harmonic operation. A new pulse magnet system is developed at FIR FU which will be able to produce the magnetic field with intensity up to 20 T and pulse length 26 ms.

In this report we present the preliminary results of mode selection in a cavity enabling stable second harmonic operation of a gyrotron at frequencies exceeding one terahertz.

2. Formalism

The equation which describes the electron motion in a gyrotron resonator can be written as follows [22]:

$$\frac{dp}{d\zeta} + \frac{i}{n} p(\Delta + |p|^2 - 1) = if(p^*)^{n-1} F \tag{1}$$

with the initial condition $p(\zeta=0) = \exp(i\upsilon_0/n)$, where υ_0 is the phase of the electron ($0 \le \upsilon_0 < 2\pi$). Here p is the dimensionless transverse momentum of the electron, $\zeta = \frac{\beta_{\perp 0}^2 \omega}{2\beta_{\parallel 0} c} z$ is the dimensionless longitudinal coordinate, $\beta_{\perp 0} = v_{\perp 0}/c$ and $\beta_{\parallel 0} = v_{\parallel 0}/c$ are the normalized transverse and parallel velocities of the electron at entrance to the cavity, $\Delta = (2/\beta_\perp^2)(\omega - \omega_c)/\omega$ is the frequency mismatch, $\omega_c = 56\pi B/\gamma_{rel}$ is the electron cyclotron frequency in GHz, B is the magnetic field in Tesla, $\gamma_{rel} = 1 + V_c/511$ is the relativistic factor, V_c is the accelerating voltage in kV. The dimensionless electron beam to RF coupling factor F is given by the expression:

$$F = \sqrt{0.00047 Q P_{out} \frac{J_{m\pm n}^2\left(\frac{2\pi}{\lambda} R_{el}\right)}{\gamma_{rel} V_c \eta_{el} \beta_{\parallel 0} \beta_{\perp 0}^{2(2-n)} \left(\nu^2 - m^2\right) J_m^2(\nu) \int_0^{\zeta_{out}} |f(\zeta)|^2 d\zeta}} \tag{2a}$$

where Q is the quality factor of the cavity, P_{out} is the output power of gyrotron in kW,

J the Bessel function, λ the wavelength, ν the eigenvalue, R_{el} the electron beam radius, and $\pm$ indicate the two possible directions of rotation of RF field (co-rotating with electrons -, and counter-rotating with the electrons +). The electron efficiency is $\eta_{el} = \dfrac{\alpha^2}{1+\alpha^2}\eta_\perp$, where $\eta_\perp$ is the perpendicular efficiency:

$$\eta_\perp = 1 - \frac{1}{2\pi}\int_0^{2\pi} |p(\zeta_{out})|^2 d\upsilon_0 \tag{2b}$$

and $\alpha = \beta_\perp/\beta_\parallel$ is the pitch factor of the electrons.

Equation (1) represents the so-called cold-cavity approximation in the gyrotron theory when RF field in a gyrotron resonator $f(\zeta)$ depends only on the geometry of the resonator, but not on the electron motion. Frequencies, diffraction quality factors and RF field profiles of specific modes calculated in the cold cavity approximation by solving the following second order differential equation [23]:

$$\frac{d^2 f}{dz^2} + k^2 f = 0 \tag{3}$$

supplemented with the boundary conditions

$$\frac{df}{dz} - ikf = 0\Big|_{z=0} \quad ; \quad \frac{df}{dz} + ikf = 0\Big|_{z=z_{out}} \tag{4}$$

Here, $k = \{\omega^2/c^2 - \nu^2/R(z)^2\}^{1/2}$ is the wave number, $\omega = 2\pi F_0(1 + i/Q_{diff})$ the complex frequency, F_0 is frequency of gyrotron oscillations, Q_{diff} the diffraction quality factor, c the velocity of light, z the longitudinal coordinate, and $R(z)$ the current cavity radius. The total quality factor Q is given by the relation $Q = Q_{diff}Q_{ohm}/(Q_{diff} + Q_{ohm})$ where $Q_{ohm} = (R_0/\delta_{skin})\{1-m^2/\nu^2\}$ is the ohmic quality factor. Here, R_0 is the radius of the middle section of the cavity, $\delta_{skin} = 0.020779\lambda$ (mm) the skin depth in the case of ideal copper at 20°, and m the azimuthal wave number of the mode.

The starting current is given by the following equation [24]:

$$I_\pm = \frac{\gamma_{rel}\beta_\parallel\beta_\perp^{2(2-n)}}{0.00047Q\sigma}\left(\frac{2^n n!}{n^n}\right)^2 \frac{(\nu^2 - m^2)J_m^2(\nu)\int_0^{\zeta_{out}}|f(\zeta)|^2 d\zeta}{J_{m\pm n}^2(2\pi R_{el}/\lambda)} \tag{5}$$

The real part of the permeability of the electron beam σ is given by the expression:

$$\sigma = -\left(n + \frac{\partial}{\partial \Delta}\right)\left|\int_0^{\zeta_{out}} f(\zeta) e^{i\Delta\zeta} d\zeta\right|^2 .$$

The gyrotron starting current is inversely proportionally to the beam-field coupling coefficient. Candidates for operating second harmonic modes are selected on the basis of the strongest coupling coefficient. From Eq. (2a) it is seen that the beam-RF field coupling for the given mode is proportional to the expression $\frac{J_{m\pm n}^{\;2}(\nu R_{el}/R_0)}{(\nu^2 - m^2)J_m^{\;2}(\nu)}$. For the fixed cavity radius R_0 the coupling can be maximized by a proper selection of the electron beam radius R_{el} which depends on the cathode radius R_{cath} of the electron gun and on the compression ratio b

$$R_b \approx R_{cath}/\sqrt{b}, \quad b = B_0/B_1 \tag{6}$$

Here B_0 and B_1 are the magnetic fields in the cavity and in the emitter region respectively [25].

In our case, R_{cath}=4.5 mm and b is around 90-125. The electron beam radius can be controlled by changing the current of additional coil at the emitter region. The maximally attainable beam radius is around 0.48 mm.

Mode competition can be studied by means of the following system of partial differential equations [26]:

$$\begin{cases} \dfrac{\partial p}{\partial \zeta} + i(|p|^2 - 1)p = i\sum\limits_s (p^*)^{n_s - 1} f_s \exp(i(\Delta_s \zeta + \psi_s)) \\ \dfrac{\partial^2 f_s}{\partial \zeta^2} - i n_s \dfrac{\partial f_s}{\partial \tau} + n_s \delta_s f_s = I_s \dfrac{1}{4\pi^2} \int\limits_0^{2\pi}\int\limits_0^{2\pi} p^{n_s} \exp(-i(\Delta_s \zeta + \psi_s)) d\theta_0 d\phi \end{cases} \tag{7}$$

supplemented by the initial and boundary conditions:

$$f_s(0,\tau) = 0, \qquad \left(f_s(\zeta,\tau) - \frac{i}{\gamma_{s,out}}\frac{\partial f_s(\zeta,\tau)}{\partial \zeta}\right)\Bigg|_{\zeta=\zeta_{s,out}} = 0$$

$$p(0) = \exp(i\theta_0) \qquad 0 \le \theta_0 < 2\pi \qquad f_s(\zeta,0) = f_{s0}(\zeta).$$

Here, $\psi_s = 8\beta_\parallel^2 \beta_\perp^{-4} (\overline{\omega}_s - \omega_c)\omega_c^{-1}\tau + (n_s \mp m_s)\phi$ is the phase of the mode, ϕ is the azimuthal coordinate, $\tau = \beta_\perp^4 \beta_\parallel^{-2} \omega_c t / 8$ is the dimensionless time, t is the real time, $\delta_s = 8\beta_\parallel^2 \beta_\perp^{-4} [\overline{\omega}_s - \omega_{s,cut}(\zeta)]\omega_c^{-1}$ describes variation of the cut-off frequency $\omega_{s,cut}(\zeta)$ along the resonator axis, $\overline{\omega_s}$ is the cut-off frequency at the exit from the resonator, and

$$I_s = 3.76 \times 10^{-3} I_0 \beta_\parallel \beta_\perp^{2(n_s-4)} n_s^3 \left(\frac{n_s^{n_s}}{2^{n_s} n_s!} \right)^2 \frac{J^2_{m_s \pm n_s}\left(\frac{2\pi}{\lambda_s} R_{el} \right)}{\gamma_{rel} J^2_{m_s}(\nu_s)(\nu_s^2 - m_s^2)} \qquad (8)$$

is the dimensionless current, where I_0 is beam current in amperes. The subscript s refers to the sth mode.

3. Mode selection

The available magnetic field around 19 T together with the beam voltage 40 kV fixes the electron cyclotron frequency at around 500 GHz. Further, the cavity radius R_0=1.95 mm (Fig. 1) and the second harmonic operation of a gyrotron at around one terahertz imply that eigenvalues of the candidate modes are in the vicinity of 41.

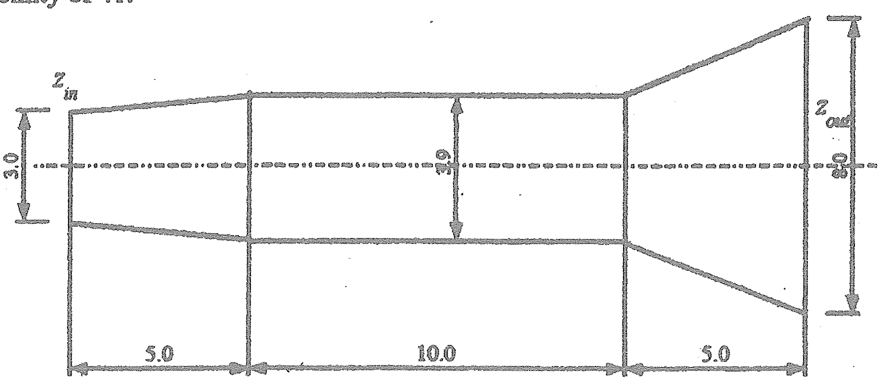

Figure 1 Cutaway view of cavity (dimension in mm)

There are several modes in this range of eigenvalues whose coupling is sufficiently large for a properly chosen beam radius (Table I).

Table I. List of possible candidate modes for the second harmonic operation.

Mode	Frequency (GHz)	Beam radius (mm)	Field in the cavity B_0 (T)	Field at the gun B_1 (T)
$TE^+_{6,11}$	1007.68	0.452	19.282	0.194
$TE^+_{4,12}$	1013.67	0.355	19.428	0.121
$TE^-_{9,10}$	1033.27	0.298	19.840	0.194

4. Starting currents

As the beam is placed at indicated positions, the candidate modes have largest possible coupling constants and the lowest possible starting currents. This is illustrated in Figs. 2-4.

$TE^{+}_{6,11}$ mode

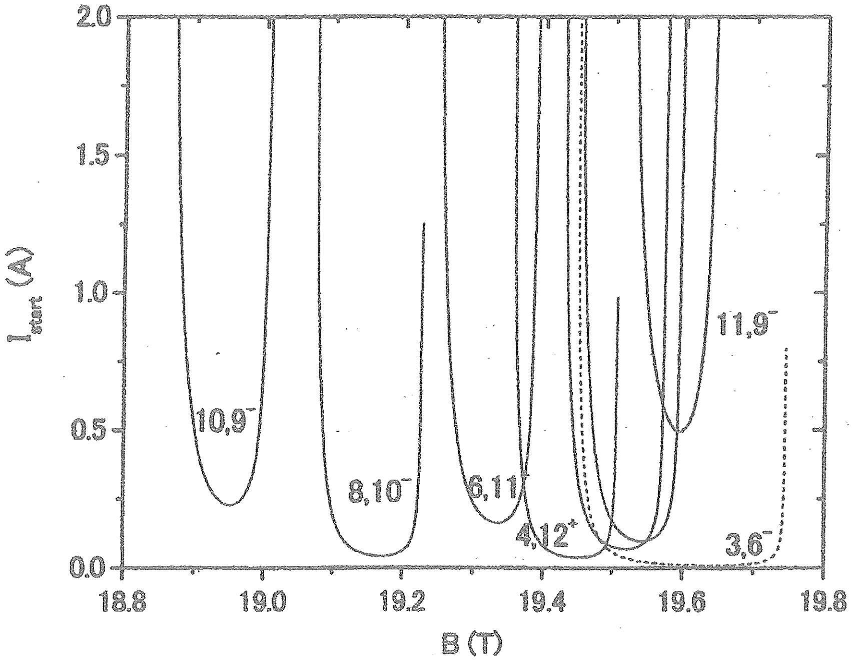

Figure 2 Starting currents optimized for excitation of the $TE^{+}_{6,11}$ mode. Here, R_{el}=0.452 mm. Solid curves show second harmonic modes, dashed curves fundamental modes, and +/- for the counter/co-rotating mode.

Fig. 2 shows that the minimum starting current of the candidate $TE^{+}_{6,11}$ mode is slightly higher than the minimum starting current of the competitor, the fundamental $TE^{+}_{3,6}$ mode. However, the starting current curves of these modes do not overlap.

TE$^{+}_{4,12}$ mode

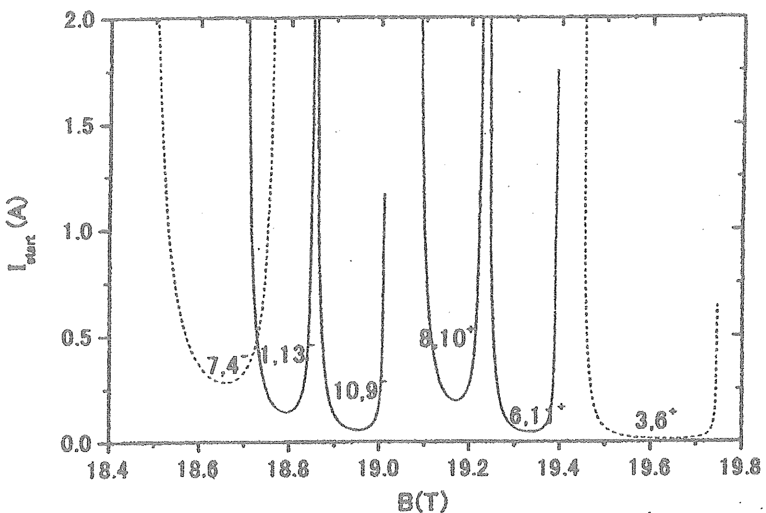

Fig. 3 Starting currents optimized for excitation of the TE$^{+}_{4,12}$ mode. Here, R_{el}=0.355 mm. Solid curves show second harmonic modes, dashed curves fundamental modes, and +/- for the counter/co-rotating mode.

It is seen in Fig. 3 that the minimum starting current of the candidate TE$^{+}_{4,12}$ mode also is slightly higher than the minimum starting current of the competitor, the first harmonic TE$^{-}_{3,6}$ mode. The situation is significantly worse than in Fig. 2, because the starting current curves of these modes overlap.

TE$^{+}_{9,10}$ mode

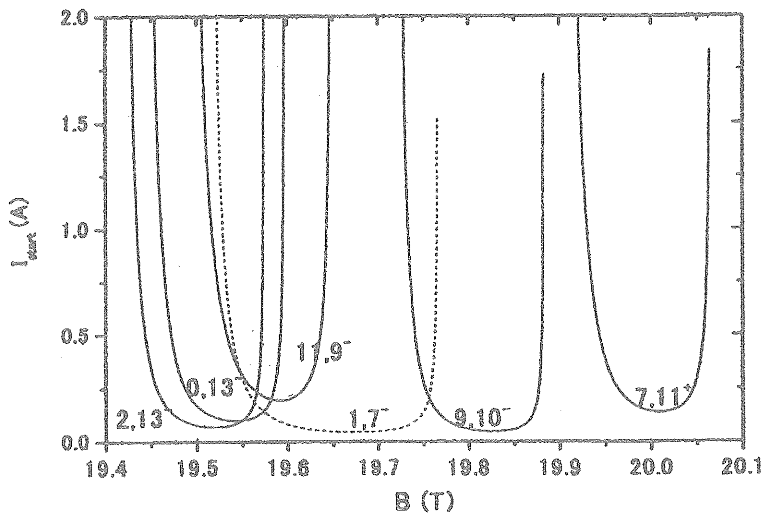

Figure 4 Starting currents optimized for excitation of the TE$^{-}_{9,10}$ mode. Here, R_{el}=0.298 mm. Solid curves show second harmonic modes, dashed curves fundamental modes, and +/- for the counter/co-rotating mode.

Fig. 4 shows that the minimum starting currents of the candidate $TE^-_{9,10}$ mode and the competitor $TE^-_{1,7}$ mode, are almost equal. Unfortunately, the starting current curves of these modes overlap.

5. Mode competition

Examination of starting current curves shown in Figs. 2-4 allows us in the first approximation to estimate chances of excitation of candidate modes. Since the starting current curves of the first candidate mode $TE^+_{6,11}$ and its main competitor $TE^+_{3,6}$ do not overlap (Fig. 2), but the two other cases $TE^+_{4,12}$ and $TE^-_{9,10}$ overlap with their competitors (Fig. 3 and Fig. 4) we can expect that the first candidate mode can be excited, whereas the second and third ones are not. To elucidate this, we have to perform mode competition calculations. The results of such calculations are shown in the figures below.

$TE^+_{6,11}$ mode

In Figure 5 we show the mode competition scenario for B_0=19.282 T and I_b=0.111 A. It can be seen that only the $TE^+_{6,11}$ mode survives.

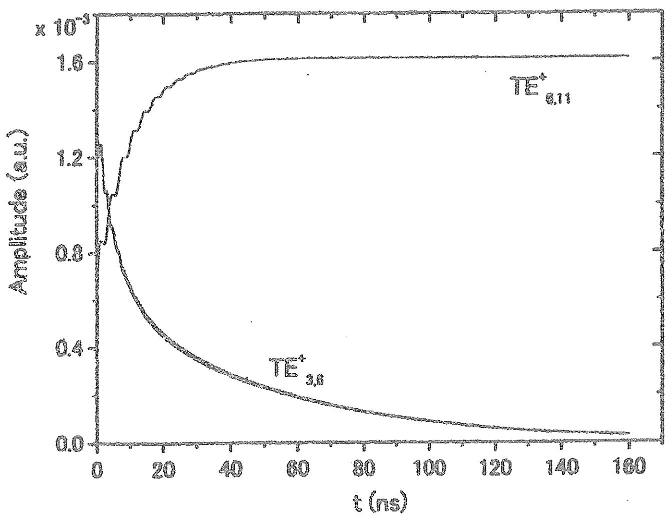

Fig. 5 Excitation of a stable $TE^+_{6\,11}$ mode. Here, B_0=19.282 T and I_b=0.111 A.

At a slightly higher operating current 0.126 A the gyrotron will oscillate in two modes simultaneously (Fig. 6). Shifting for a slightly higher magnetic field 19.346 T and at the beam current 0.24 A the first harmonic mode $TE^+_{3,6}$ wins the competition (Fig. 7).

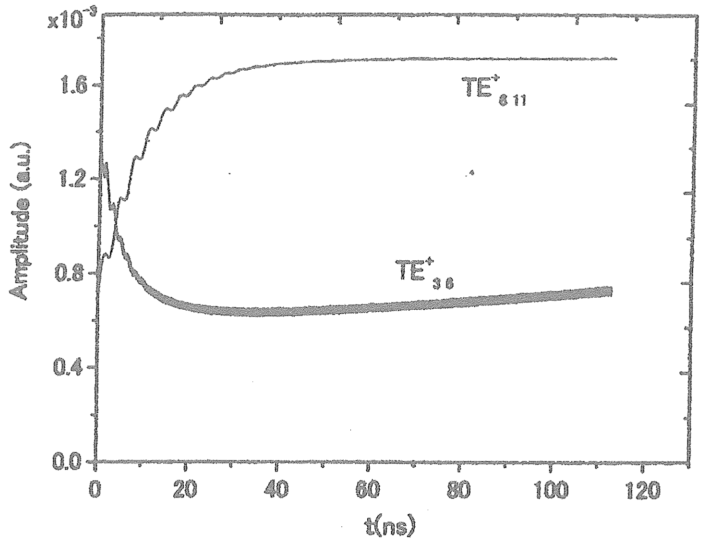

Fig. 6 Simultaneous excitation of two modes. Here, B_0=19.282 T and I_b=0.129 A

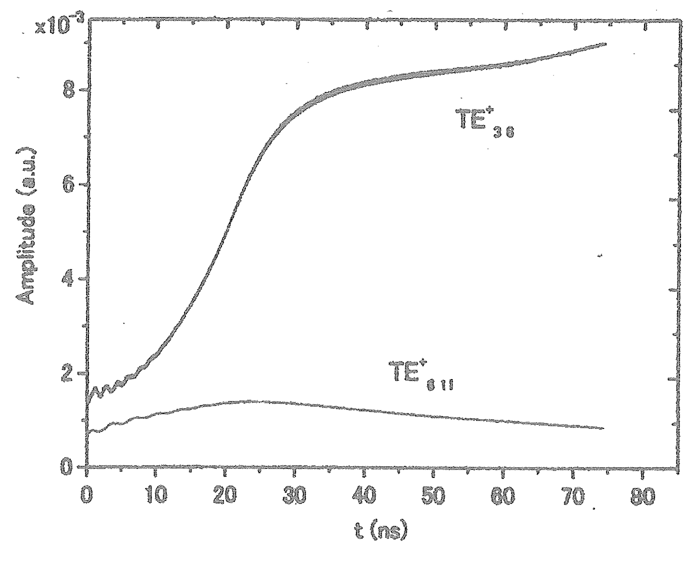

Fig. 7 Excitation of the first harmonic $TE^{+}_{3,6}$ mode. Here, B_0=19.346 T and I_b=0.24 A

The dependence of the output power and efficiency on the beam current is shown in Fig. 8. This calculation was performed for the beam voltage 40 kV, beam radius 0.452, magnetic field in cavity 19.282 T and the pitch factor 1.55. It is seen that due to the mode competition it is not possible to achieve the maximum efficiency (~0.11) and the maximum output power (~2 kW) at the beam current ~0.2 A.

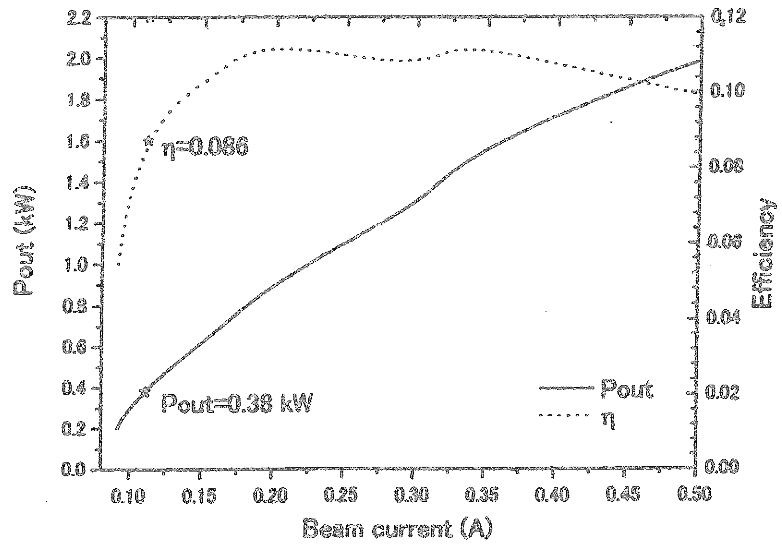

Fig. 8 Output power and efficiency as a function of the electron beam current.

$TE^{+}_{4,12}$ mode

Some possibilities to establish this mode by adjustment magnetic field on the region of minimum starting current and selection of some possible beam currents have done in the mode competition calculation but this candidate can not be excited. Fig. 9 shows one of them, this candidate mode is loosing competition.

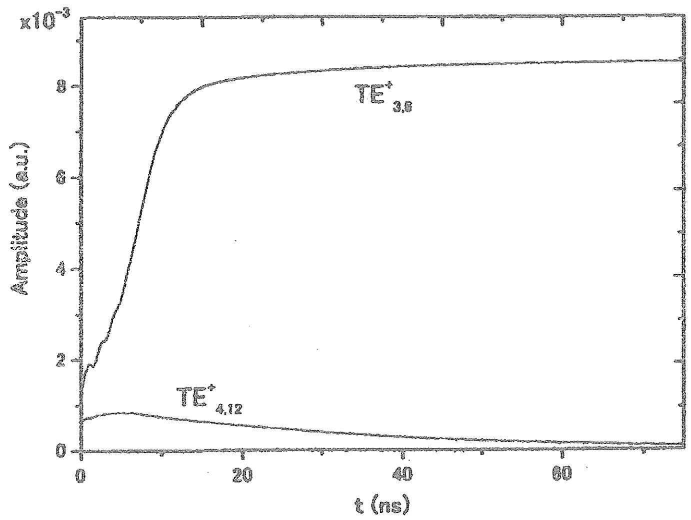

Fig. 9 Excitation of the first harmonic $TE^{+}_{3,6}$ modes. Here B_0=19.42 T and I_b=0.16 A

$TE^{+}_{9,10}$ mode

Although the minimum starting current of the $TE^{+}_{9,10}$ mode is almost same as the starting current of the $TE^{-}_{1,7}$ mode, mode competition calculations show that it cannot be excited (Fig.10 and Fig. 11).

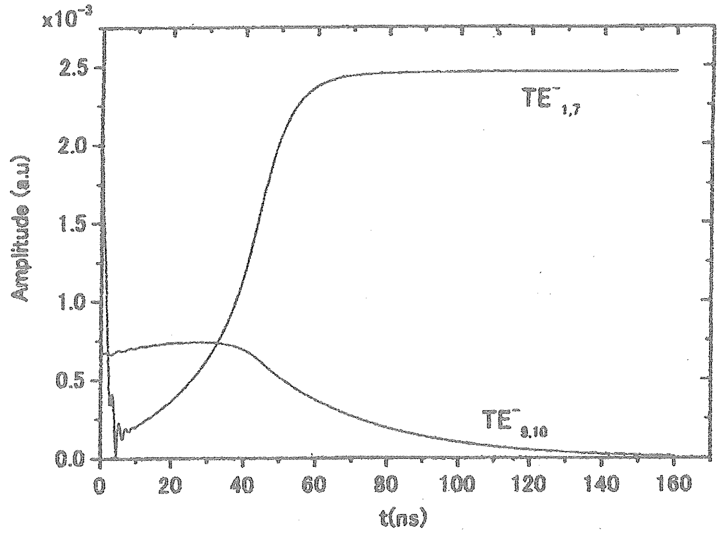

Fig. 10. Mode competition between the second harmonic $TE^{-}_{9,10}$ mode and the fundamental $TE^{-}_{1,7}$ mode at B_0=19.84 T and beam current 0.05A.

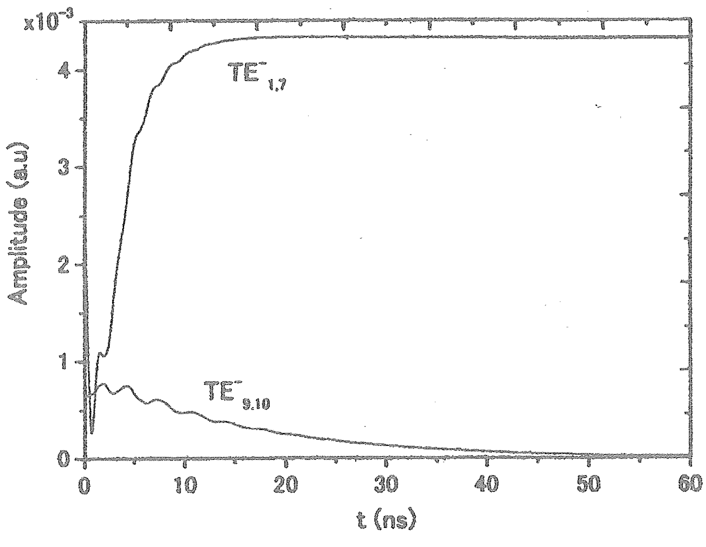

Fig. 11 Mode competition between the second harmonic $TE^{-}_{9,10}$ mode and fundamental $TE^{-}_{1,7}$ mode at B_0=19.84 T and beam current 1.8A.

6. Conclusions

Mode competition calculations have shown that in the existing cavity only one candidate mode, $TE_{6,11}$, has passed the selection criterion. The proposed parameters of the terahertz gyrotron are summarized in Table II.

Table II. Design parameters of a second harmonic terahertz gyrotron.

Cavity mode : $TE^{-}_{6,11}$
Cavity radius R = 1.95 mm
Cavity (interaction) length L =10 mm
Quality factor Q = 23365
Electron beam radius R_{el} = 0.452 mm
Electron beam current I_b = 0.111 A
Operating frequency f = 1007.68 GHz
Magnetic field in the cavity B_0 = 19.282 T
Magnetic field at the emitter B_1 = 0.194 T
Beam voltage V_c = 40 kV
Anode voltage V_a = 34.3 kV
Electron pitch factor α = 1.55
Electronic efficiency η = 8.6%
Output power $Pout$ = 0.38 kW

It is interesting to note that in principle the perpendicular efficiency of a gyrotron operating at the second harmonic can be as high as 57% [27] for optimum values of generalized parameters: the normalized beam current I=0.04 and the normalized cavity length μ=16.75. However, in our case μ=51.3 and I=0.00035 which is far away from the high efficiency region. To obtain higher efficiencies of about 30% it would be sufficient to shorten the existing cavity from its present length 10 mm to about its half 5 mm. Mode competition should be recalculated.

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