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Dual frequency gyrotron operating at 42/84 GHz for plasma fusion application

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ABSTRACT

The design study of dual frequency gyrotron operating at 42/84 GHz frequencies with output power ~500 kW is presented in this article. $TE_{10,4}$ and $TE_{6,2}$ are selected as the operating modes for 84 and 42 GHz operations of the device, respectively. The beam-wave interaction simulations are performed by using the Particle-in-Cell algorithm to evaluate the growth of RF power and frequency. Magnetically tunable magnetron injection gun is also designed to launch the electron beam at the radius of 6.2 mm (84 GHz) and 7.3 mm (42 GHz) in the interaction cavity. The CVD diamond RF window is also designed, which must be transparent for 42 GHz and 84 GHz frequencies. The design results of the dual frequency gyrotron confirm the growth of ~500 kW power at 42/84 GHz.

1. Introduction

The gyrotron oscillator is a vacuum electronic device based on the phenomena of cyclotron maser instability occurs due to the electromagnetic perturbation in the gyrating electron beam in the presence of external uniform magnetic field [1]. The gyrating electron beam is generated from the conical shaped cathode and passes through the crossed electric and magnetic fields towards a nearly uniform waveguide section where the interaction takes place with electromagnetic wave at near cutoff [2,3]. The invention of gyrotron as a device was motivated by the plasma fusion community due to the requirement of high power, high frequency source in controlled plasma fusion [3]. At present, gyrotron is a signature device in plasma fusion and diagnosis and a detail review of the development of fusion gyrotrons is given in Refs. [4–7]. Rather than the application in controlled plasma fusion, gyrotron is also explored in several other potential applications such as DNP-NMR spectroscopy, security, material processing, etc., [8–10]. At present the gyrotron development is going mainly into two directions, one is very high power millimeter wave gyrotrons for plasma fusion and second is medium *or* low power sub-TH/THz gyrotrons.

In several plasma fusion machines, such as ASDEX, SST-1, JT-60, etc., two or more frequencies are used in millimeter wave band for electron cyclotron resonance heating (ECRH) and current drive of magnetically confined plasma [11–14]. Corresponding to each frequency, the gyrotron oscillators are used to supply the RF power in the power range of several hundred kW to MW. Considering the use of two or more frequencies in ECRH system, recently, the development efforts are started in the direction of multi-frequency gyrotrons, which further leads toward the overall simplification of the heating system [15–20]. The experimental results of dual frequency (117 GHz/170 GHz & 28 GHz/35 GHz) fusion gyrotrons are reported recently [14,16], which further concrete the possibilities of such gyrotrons for very high power generation. Considering the advantages of dual frequency gyrotron, the design and feasibility study of 42/84 GHz gyrotron is carried out and presented here. These frequencies are applicable in the Indian tokamak system (ADITYA and SST-1) for ECR heating. The design study of electron beam source for 42/84 GHz dual frequency gyrotron is also performed recently by S. Sawant et al. and the results are described in Ref. [21].

The design specifications of 42/84 GHz gyrotron are given in Table 1. For 42&84 GHz frequencies, TE modes are selected

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Table 1
Design specification of 42/84 GHz gyrotron.

Frequency (f)	84&42 GHz
Output power (P_{out})	≈500 kW
Harmonic (s)	1
Beam voltage (V_b)	78–82 kV
Beam current (I_b)	14–16 A
Interaction efficiency (η)	≥35%

considering both the modes must support same interaction cavity and mode converter. The mode selection, start oscillation current calculations and cold cavity analysis are discussed in detail in section 2. The Particle-in-Cell (PIC) simulations of beam-wave interaction [22–24] are performed to calculate the RF power and frequency and discussed in Section 3 of the manuscript. The magnetically tunable magnetron injection gun (MIG) [18,25] is designed to launch the electron beam at two different radii (calculated according to selected TE modes for 42 and 84 GHz operations) in the interaction cavity and discussed in section 4. Finally, CVD diamond disk window [4,26–28], which must be transparent for 42&84 GHz frequencies, is designed and discussed in section 5. All the results are concluded in the last section.

2. Mode selection and cold cavity analysis

The operating mode selection is a critical issue in the gyrotron design because the overall performance of the device deeply depends on the selected operating mode. In case of dual frequency gyrotron, the operating mode selection becomes more critical because both the modes (corresponding to 42 GHz and 84 GHz operations) must be acceptable by interaction cavity, mode convertor and RF window. To fulfill this requirement, the following equations must be satisfied by both the modes and frequencies:

$$\frac{f_1}{f_2} = \frac{\chi_{mn1}}{\chi_{mn2}} \tag{1}$$

$$\frac{m_1}{m_2} \approx \frac{\chi_{mn1}}{\chi_{mn2}} \tag{2}$$

$$\lambda = \frac{2\sqrt{\varepsilon_r'}\cdot t}{n} \tag{3}$$

Here, f_1, f_2, χ_{mn1}, χ_{mn2}, m_1, m_2, ε_r, λ, t and n are first frequency, second frequency, Bessel function derivative root of first mode, Bessel function derivative root of second mode, azimuthal index of first mode, azimuthal index of second mode, dielectric constant of window material, wavelength of corresponding frequency, thickness of RF window and integer, respectively. During the mode selection procedure, various design and technical constraints such as voltage depression (V_d), limiting current (I_L), ohmic wall loss (dP/dA), mode competition, etc., are also considered and discussed elsewhere in detail [29–32]. First, the suitable transverse electric (TE) modes are searched for 84 GHz operation of the device and the selected modes are described in Table 2. The interaction cavity radius (R_c) and beam radius (R_b) are calculated by using the expressions $R_c = \chi_{m,p}\lambda/2\pi$ and $R_b = \chi_{m\pm s,i}\lambda/2\pi$, respectively [29,30]. The most dangerous competing modes for any $TE_{m,n}$ mode are $TE_{(m-3),(n+1)}$ and $TE_{(m-1),n}$ and thus the frequency separation of the operating mode from these modes must be as large as possible [33]. The frequency separations $\Delta f_1 = [\chi_{m,p} - \chi_{(m-3),(p+1)}]/\chi_{m,p} \times 100\%$ and $\Delta f_2 = [\chi_{m,p} - \chi_{((m-1),p)}]/\chi_{m,p} \times 100\%$ of the operating mode from these modes are also calculated and shown in Table 2. Finally, $TE_{10,4}$ is selected as the operating mode for 84 GHz operation as it satisfies all the design and technical constraints.

Table 2
Mode selection parameters for suitable modes for 84 GHz frequency.

Mode	χ_{mn}	V_d (kV)	I_L (A)	dP/dA (kW/cm^2)	m/χ_{mp}	Δf_1	Δf_2
$TE_{7,5}$	23.30	2.40	63.03	0.77	0.30	3.86	6.05
$TE_{8,4}$	21.22	2.11	71.60	0.99	0.37	3.03	5.92
$TE_{8,5}$	24.58	2.56	58.98	0.71	0.32	3.16	5.19
$TE_{9,4}$	22.50	2.29	66.00	0.90	0.40	2.68	5.64
$TE_{10,3}$	20.22	1.96	77.06	1.24	0.49	1.27	6.01
$TE_{10,4}$	23.76	2.46	61.50	0.83	0.42	1.91	5.29
$TE_{11,3}$	21.43	2.14	70.63	1.13	0.51	0.93	5.63

Further, keeping the interaction cavity dimension fixed, χ_{mn2} of the operating mode for 42 GHz operation is calculated by putting $f_1 = 84$ GHz, $f_2 = 42$ GHz and $\chi_{mn1} = 23.76$ in equation (1). Four TE modes ($TE_{1,4}$, $TE_{3,3}$, $TE_{6,2}$ and $TE_{10,1}$) are found suitable around $\chi_{mn2} = 11.8$ and all the mode selection parameters for these modes are summarized in Table 3. $TE_{6,2}$ is finalized for the 42 GHz operation. It is worthy to mention here that both $TE_{10,4}$ and $TE_{6,2}$ modes are satisfying equation (1), which indicates that the single interaction cavity would support both the modes during beam-wave interaction. It is mandatory that both the selected operating modes must exhibits approximately the same radiation angle ($\theta_r = \cos^{-1}(m/\chi_{mn})$) to support the mode launcher [15]. The calculated radiation angles for $TE_{10,4}$ and $TE_{6,2}$ modes are 64.5° and 60° which indicate that both the modes can support single mode launcher [34].

Further single mode linear theory is used to evaluate the mode competition [35,36]. Considering this theory, start oscillation currents are calculated for the selected and neighboring competing modes by using an in-house developed computer code GCOMS [37] and the results are shown in Fig. 1. Results show that $TE_{7,5+}$ and $TE_{3,3+}$ are the most competing modes for the operating modes $TE_{10,4}$ and $TE_{6,2}$, respectively. In Fig. 1, '+' and '−' signs represent counter and co-rotating direction of the electric field inside the interaction cavity. The coupling coefficients for the operating modes and most competing modes are also calculated to evaluate the beam launching position in the interaction cavity precisely [38]. Fig. 2 shows the results of beam-wave coupling coefficient with respect to the beam launching position normalized to the cavity radius. A range of beam launching position (dashed lines) is also shown in figure considering the maximum coupling strength without interruption of any competing modes. The beam launching positions for 84 GHz and 42 GHz operations are decided 6.2 mm and 7.3 mm, respectively.

The interaction cavity used in the gyrotron is a three section circular waveguide consist a cutoff down taper, a straight circular waveguide (also called middle section) and an output taper. The middle section radius is calculated according to the selected operating mode. The middle section length, down taper angle and up-taper angle are optimized in the cold cavity analysis by using the CASCADE code [39]. Q factor and wall loss are two major parameters of the cavity design and taken into consideration during the cold cavity simulations. Fig. 3 shows the variation in Q factor and wall loss with respect to the middle section length and output taper angle. Higher Q leads towards the higher wall loss and lower Q of

Table 3
Mode selection parameters for suitable modes for 42 GHz frequency.

Mode	χ_{mn}	V_d (kV)	I_L (A)	dP/dA (kW/cm^2)	m/χ_{mp}
$TE_{1,4}$	11.70	1.85	81.54	0.16	0.08
$TE_{3,3}$	11.34	1.76	86.00	0.18	0.26
$TE_{6,2}$	11.69	1.85	81.66	0.21	0.51
$TE_{10,1}$	11.77	1.87	80.80	0.56	0.84