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Design of 42 GHz gyrotron for Indian fusion tokamak system

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HIGHLIGHTS

- The complete electrical design of 42 GHz, 200 kW gyrotron is presented.
- Un-depressed collector and axial output system for RF power is selected.
- Various commercially available design tools as well as in-house developed computer codes are used in the design process.
- The experimental results of cold cavity analysis are also presented.
- The design results show more than 200 kW power with 40% interaction efficiency at 42 GHz frequency.

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ABSTRACT

In this paper, the complete design of a 42 GHz, 200 kW gyrotron at first harmonic operation for Indian tokamak system is presented. The gyrotron is designed for $TE_{0,3}$ operating mode. Un-depressed collector and axial output system for RF power is selected just due to the sake of simplicity in the actual fabrication of the device as it is the first design and development experience. Various commercially available design tools as well as in-house developed computer codes are used in the design process. The experimental results of cold cavity analysis are also presented in this manuscript. The rigorous design simulations confirm more than 200 kW RF power generation in $TE_{0,3}$ mode at 42 GHz frequency.

1. Introduction

In order to fulfill the future energy need, research on the controlled thermonuclear fusion at the energy generation level is going on extensively worldwide [1]. The fuel plasma is confined in a special kind of magnetic field arrangement called *tokamak* and heated up to very high temperature so that the nuclear fusion reaction get started. Gyrotron oscillators are high-power microwave sources used for plasma heating (mainly electron cyclotron resonance heating *or* ECRH) and plasma stabilization through localized current drive in magnetically confined plasmas for controlled thermonuclear fusion experiments [2]. Other than the plasma heating, the device is also used commonly in Nuclear Magnetic Resonance (NMR) spectroscopy for biological imaging, material processing, high speed communication, etc. [3]. The present status of the gyrotron development including fusion gyrotrons is described in [4].

The research on the controlled plasma fusion in India is going on at Institute of Plasma Research (IPR) Gandhinagar, where two tokamak systems namely ADITYA and SST-1 were developed [5,6]. Considering the requirement of gyrotron in ADITYA and SST-1 tokamak systems, a program of design and development of a 42 GHz, 200 kW gyrotron was initiated, which is now in development phase. We report in this manuscript on the complete design of CW 42 GHz, 200 kW gyrotron for plasma fusion application. The linear output system (non linear taper) and un-depressed collector are designed in place of radial output system (quasi optical mode launcher) and depressed collector due to just simplicity as it is our first experience in gyrotron on the development level. Thermo-mechanical analysis of the complete device is omitted here just due to the sake of briefness and only the electromagnetic design is presented. The basic design goals are given in Table 1. To complete the design task, various in-house developed as well as commercially available computer codes were used (described in the successive sections). The

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Table 1
Design goals.

Frequency (f)	42 GHz
Output power (P)	200 kW, CW
Beam voltage (V_b)	60–70 kV
Beam current (I_b)	≈10 A
Beam velocity ratio (α)	1.3–1.4
Total efficiency (η)	>30%

design results show more than 200 kW power with 40% interaction efficiency at 42 GHz frequency.

2. Mode selection and start oscillation current computation

The operating mode selection is performed by considering the various issues, like, minimum mode competition, minimum ohmic wall loss and minimum space charge effect. Various transverse electric (TE) modes are studied by using in-house developed computer code GCOMS. The cavity radius ($R_c = \chi_{m,n}\lambda/2\pi$) and the beam radius ($R_b = \chi_{m\pm n,i}\lambda/2\pi$) are calculated for the various suitable cavity modes, where $\chi_{m,n}$ is the nth root of the Bessel function derivative $J'_m(x) = 0$, λ is the free space wavelength ($\lambda = 7.14$ mm corresponding to operating frequency) and for first harmonic operation $i = 1$. The space charge effects (in terms of voltage depression, V_d and limiting current, I_L) [7] and ohmic wall loss (dP/dA) [8] are calculated for the various suitable modes by using GCOMS and summarized in Table 2. For the CW operation of the tube, the ohmic wall loss should not exceed 1 kW/cm^2 and this is considered a main mode selection constraint. The electrical properties of high quality Oxygen Free High Conductivity (OFHC) copper are used in the calculations of ohmic wall loss. The space charge effects must also be within a limit. A limit of voltage depression (V_d < 10% V_b) and limiting current ($I_L > 2I_b$) is considered here and incorporated in the GCOMS. All the modes shown in Table 2 fulfill the mode selection criteria. However, the symmetric modes TE_{02} and TE_{03} are considered for further analysis due to the simplicity and ease of excitation in cavity. The voltage depression is much higher in case of beam launching position at first radial maxima for both the modes and thus the second maximum is selected as the beam launching position. Further, the gap between cavity wall and electron beam for TE_{02} mode is very small (Table 2) and thus this mode is rejected in favor of TE_{03}. TE_{03} mode has been used successfully in some gyrotron experiments described in Refs. [9,10], which also gave confidence to select this mode.

The start oscillation current (SOC) is calculated by using GCOMS for the operating mode and the neighboring modes lies in the amplification band $\Delta\omega = \pi/T$ [11], where T is the transient time of the electrons through the resonator cavity. The starting current is calculated by using linearized single-mode theory and described in detail elsewhere [12]. In the SOC calculations, the electron beam is launched at second radial maxima of $TE_{0,3}$ mode. Fig. 1 shows the start oscillation current curves for the operating mode and neighboring competing modes. $TE_{2,3}$ is the most competing mode for the operating mode. It has also been explained in Ref. [13], the symmetric operating modes with $p \geq 3$ mainly suffered from mode competition with $TE_{2,p}$ mode. In the current gyrotron design, the operating mode is well separated from the competing modes in the range of operating magnetic field (1.61–1.64 T).

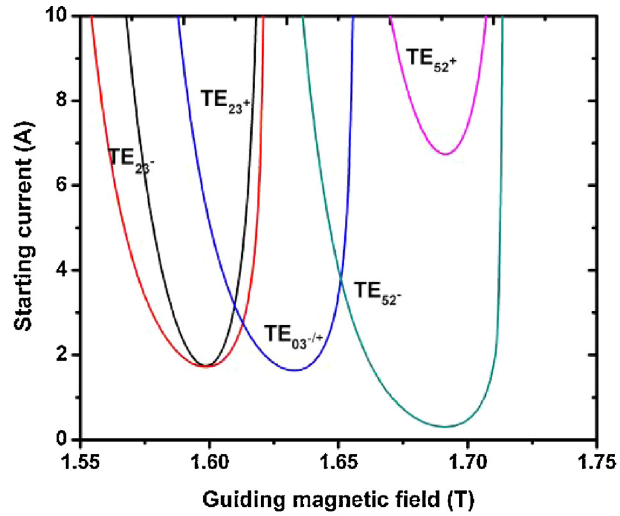

Fig. 1. Starting current for various modes (V_b = 65 kV, I_b = 10 A, α = 1.4, R_b = 6.06 mm and R_c = 11.57 mm).

3. Cavity design

3.1. Cold cavity analysis and mode identification

The simple cylindrical open ended resonator cavity is designed for the 42 GHz gyrotron. Such types of cavities consist three sections: middle section (for beam–wave interaction), input down taper (for cutoff section) and output up taper (for traveling wave section). The cold cavity analysis (mode identification, axial field profile and Q factor) is performed numerically as well as experimentally. Particle-in-Cell code MAGIC is used for the numerical simulations [14,15]. A very fine grid size (Δr = 0.2 mm, Δphi = 20°, Δz = 0.2 mm) is used in the simulation process. The input taper and output taper angles are optimized considering the Gaussian type of electric field profile and Q factor as main parameters. The optimized interaction cavity geometrical parameters for the operating mode TE_{03} are summarized in Table 3. The experimental methods used for the mode identification and Q factor measurement are described in Refs. [16,17] and not discussed here in detail. The interaction cavity with the dimensions described in Table 3 is fabricated within the tolerance of ±0.01 mm and used in the experiments. The same structure is also simulated in PIC code for the eigenmode, resonant frequency and Q factor analyses. A Vector Network Analyzer (VNA) of frequency range from 200 MHz to 50 GHz is used in the

Table 2
Calculated mode selection parameters.

Mode ($TE_{m,p}$)	χ_{mp}	R_c (mm)	R_b (mm)	ΔV (kV)	I_L (A)	dP/dA (kW/cm^2)
TE_{22}	6.706	7.627	2.09	2.89	30.1	0.125
TE_{02}	7.016	7.980	2.09	2.99	29.1	0.104
TE_{02}[a]	7.016	7.980	6.05	0.51	138.1	0.104
TE_{52}	10.520	11.965	6.05	1.53	57.0	0.060
TE_{33}	11.350	12.909	7.62	1.178	72.8	0.050
TE_{23}	9.969	11.339	2.09	2.89	30.1	0.054
TE_{03}	10.173	11.571	2.09	3.82	22.8	0.049
TE_{03}[a]	10.173	11.571	6.06	1.44	59.0	0.049
TE_{42}	9.282	10.557	7.78	1.77	49.1	0.073

[a] Beam is launched at second radial maxima.