Infrared Physics & Technology 57 (2013) 1–7

Contents lists available at SciVerse ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Towards a 1 MW, 170 GHz gyrotron design for fusion application

Anil Kumar *, Nitin Kumar, Udaybir Singh, Ranajoy Bhattacharya, Vivek Yadav, A.K. Sinha

Gyrotron Laboratory, Microwave Tube Division, CSIR-Central Electronics Engineering Research Institute (CEERI), Pilani, Rajasthan 333 031, India

HIGHLIGHTS

- ▶ The complete electrical design of different component for high power and high frequency gyrotron.
- ▶ $TE_{34,10}$ mode is selected as the operating mode.
- ▶ The single stage depressed collector is designed to increase the overall efficiency of the gyrotron.
- ▶ The overall tube efficiency more than 55% with SDC.

ARTICLE INFO

Article history:
Received 19 July 2012
Available online 28 November 2012

Keywords:
Gyrotron
Electron gun
MIG
Interaction cavity
Depressed collector
RF window

ABSTRACT

The electrical design of different components of 1 MW, 170 GHz gyrotron such as, magnetron injection gun, cylindrical interaction cavity and collector and RF window is presented in this article. Recently, a new project related to the development of 170 GHz, 1 MW gyrotron has been started for the Indian Tokamak. $TE_{34,10}$ mode is selected as the operating mode after studied the problem of mode competition. The triode type geometry is selected for the design of magnetron injection gun (MIG) to achieve the required beam parameters. The maximum transverse velocity spread of 3.28% at the velocity ratio of 1.34 is obtained in simulations for a 40 A, 80 kV electron beam. The RF output power of more than 1 MW with 36.5% interaction efficiency without depressed collector is predicted by simulation in single-mode operation at 170 GHz frequency. The simulated single-stage depressed collector of the gyrotron predicted the overall device efficiencies >55%. Due to the very good thermal conductivity and very weak dependency of the dielectric parameters on temperature, PACVD diamond is selected for window design for the transmission of RF power. The in-house developed code MIGSYN and GCOMS are used for initial geometry design of MIG and mode selection respectively. Commercially available simulation tools MAGIC and ANSYS are used for beam–wave interaction and mechanical analysis respectively.

1. Introduction

The energy generation by magnetically confined plasma fusion is a major research area among the plasma physics/nuclear fusion community. The nuclear fuel is heated up to a very high order critical temperature to initiate the nuclear reaction by various heating methods such as, neutron beam injection (NBI), ion cyclotron heating (ICH), lower hybrid heating (LHH), and electron cyclotron heating & current drive (ECH&D). Electron cyclotron resonance heating in a magnetically confined plasma requires tens of megawatt of electromagnetic radiation in millimeter wave band (generally >100 GHz) [1,2]. Gyrotron, based on the Cyclotron Resonance Maser (CRM) instability phenomena, is an efficient and powerful source of electromagnetic radiation in the millimeter wave band and is used almost in all ECH&D systems [3,4]. About 170 GHz has been decided the ECRH frequency for the International Thermonuclear Experimental Reactor (ITER) and total 20 MW CW power will be delivered to the ECH&D system [5]. In order to deliver the required 20 MW of power into the plasma, the common output power of the gyrotrons will be 24 MW at 170 GHz frequency. Several research groups around the globe are working towards the development of 170 GHz gyrotron with output power of 1 MW or more. A cylindrical cavity resonator based conventional 170 GHz gyrotron with 1 MW of RF power is developed by Russian and Japanese researchers [6,7]. The Japanese gyrotron has demonstrated 1 MW output power for 800 s and 0.8 MW power for 1 h [6]. The Russian gyrotron shows the capability of 1 MW power for 570 s and 0.8 MW power for 1000 s [6]. The research groups in Europe are trying to develop a coaxial cavity based 170 GHz gyrotron with ⩾2 MW RF power from a single tube to reduce the total number of gyrotron units in the ITER ECH&D system [7,8]. The experimental results of European coaxial gyrotron show 2.2 MW power in the short pulse regime (∼1 ms) [6,8].

* Corresponding author.
E-mail address: anil.gyrotron@gmail.com (A. Kumar).

1350-4495/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.infrared.2012.11.006

Table 1
The design specifications of gyrotron.

Frequency (f)	170 GHz
Output power (P_{out})	⩾1.0 MW
Efficiency with SDC (η)	⩾50%
Beam voltage (V_b)	78–82 kV
Beam current (I_b)	38–42 A
Velocity ratio (α)	~1.35
Ohmic wall loss	<1 kW/cm^2
Quality factor	800–1400

Considering the importance of 170 GHz frequency in the futuristic fusion tokamak systems for energy generation, a new project related to the design and development of 170 GHz, 1 MW CW gyrotron tube is initiated in India for the Indian Tokamak sponsored by CSIR. In the continuation of this project the design work of different components of 170 GHz, 1 MW is accomplished and discussed in detail in this manuscript. In this article the design results of major components of 170 GHz, 1 MW gyrotron is presented. The development statuses and testing setup of the device are in initial stage. The design specifications of this gyrotron are summarized in Table 1. Various indigenously developed and commercially available computer tools are used in the designing and discussed in the successive sections. The paper is divided into six sections. In Section 2, the mode selection and cold cavity analysis is presented. Simple cylindrical open resonator type of structure consisting a cutoff input taper section, a straight middle section and a traveling output taper section is considered in this gyrotron. A very high-order volume mode is selected to keep the ohmic wall losses in the cavity within a limit shown in Table 1. The beam–wave interaction simulations and the analysis of output power and frequency growths are described in Section 3. Particle-in-Cell (PIC) algorithm based code is used in the beam–wave interaction simulations [9]. The beam parameters optimization and parametric analysis are also performed in this section. In the Section 4, 2-D and 3-D design of triode type magnetron injection gun (MIG) are described. Single stage depressed collector (SDC) is designed to enhance the overall efficiency of tube and presented in the Section 5. For the extraction of generated RF power, PACVD diamond window will be used due to the excellent dielectric and thermo-mechanical properties of PACVD diamond material. The optimization of window disk thickness and diameter is also discussed in Section 5.

2. Mode selection and cold cavity analysis

The high order asymmetric TE modes (eigenvalues $\chi_{m,p} > 55$) are analyzed for the 170 GHz gyrotron to enhance the interaction cavity volume or to reduce the ohmic wall loading. For the high order mode, the mode competition becomes severe and a careful investigation is needed to separate out the competing modes from the operating mode [10]. The GCOMS code [11,12] is used to find one mode which is suitable to deliver the desired output power within a broad range of operating parameters. Various high order modes are studied on the basis of operating mode selection parameters such as, space charge effect (voltage depression V_d and limiting current I_L) [13], ohmic wall loss dP/dA [14], and frequency separation from the most competing modes (Δf_1 and Δf_2) [10] and summarized in Table 2. Within this procedure $TE_{34,10}$ mode showed very promising behavior concerning wall loses, space charge effect, reliable output power, mode competition, efficiency and stability. The cavity radius (R_c) and beam radius (R_b) are calculated for the operating mode, which are 20.95 mm and 10 mm, respectively. The beam launching position is selected at the corotating first radial electric field maxima of the operating mode for better beam–wave coupling. The proper launching of the electron beam is very necessary so that the beam can be coupled only with the desired operating mode. The output taper angle (θ_2) and cavity middle section length (L) are optimized considering a reasonable value of Q (generally considered 800–1400 for fusion gyrotrons). The total Q for the gyrotron resonator cavity is given by [14,15]:

$$\frac{1}{Q} = \frac{1}{Q_{diff}} + \frac{1}{Q_{ohm}}$$

The diffractive quality factor (Q_{diff}) and ohmic quality factor (Q_{ohm}) are caused by the diffraction losses and ohmic losses, respectively and can be calculated by the equation given below:

$$Q_{diff} = \frac{Q_{diff,\,min}}{1-\rho} = \frac{4\pi}{(1-\rho)}\left(\frac{L}{\lambda}\right)^2$$

$$Q_{ohm} = \frac{R_c}{\delta}\left(1 - \frac{m^2}{\chi_{m,p}^2}\right)$$

where $\rho = R_1R_2$, R_1 and R_2 are the reflections at both the ends and δ is the skin depth of cavity wall which depends on the material conductivity and frequency.

Further the Cascade code [16] is used for the calculation of Q and optimization of output taper angle and the cavity middle section length. The ohmic wall loss is a critical parameter in the designing of high power gyrotrons and thus it is also analyzed for the various values of θ_2 and L. Fig. 1a and b shows the Q and dP/dA versus θ_2 and L, respectively. The ohmic wall loss is calculated by the equation given below [14]:

$$\frac{dP}{dA} = 2\pi\sqrt{\frac{1}{\pi Z_0 \sigma}}\frac{P_{out}Q_{diff}}{L\lambda^{1.5}}\frac{1}{\chi_{m,n}'^2 - m^2}$$

where Z_0, σ and P_{out} are the free space impedance, conductivity of cavity material and the generated power in the cavity (considered 1 MW here). In order to obtain the enough output power and minimum wall losses, θ_2 and L are optimized as 3° and 13 mm, respectively. Table 3 shows the optimized cavity geometry parameters for selected operating mode. The ohmic wall loss, which is a main concern in MW fusion gyrotrons, is under technical limit (<1 kW/cm^2) for the optimized cavity geometry. Fig. 2a shows the normalized electric field profile for the optimized cavity geometry given in Table 3.

The start oscillation current curves for the operating mode and the neighboring competing modes are obtained by using the theory described in detail elsewhere [17,18] (by using GCOMS). Fig. 2b shows the start oscillation current curves for the operating mode and its neighboring modes, respectively. The optimum operation point is found in the deep hard excitation region, which was attained by active control of the cavity magnetic field and the perpendicular to parallel velocity ratio factor of the electron beam. In this hard excitation region, $TE_{33,10}$ gives maximum mode competition to the operating mode. The $TE_{33,10}$ mode shows approximately similar starting condition as the operating mode. To avoid the excitation of this mode, proper launching of the electron beam is very necessary so that the beam can coupled only with the desired operating mode.

3. Beam–wave interaction analysis

The beam–wave interaction analysis is carried out after mode selection and cold cavity analysis. The beam–wave interaction simulations are carried out using 3D particle-in-cell (PIC) electromagnetic simulation code, MAGIC [9,19]. The MAGIC code is executed by using the Maxwell Centered algorithm for the relativistic electron beam–wave interaction, which yields no damping at any fre-