ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 5, Issue 6, November 2016

Design and Development of Cavity for High Power Gyrotron

MK Alaria, Y Choyal[#] and AK Sinha
Gyrotron Laboratory
Central Electronics Engineering Research Institute (CSIR-CEERI) Pilani,
Rajasthan, India, PIN-333031
School of Physics, DAVV, Indore, India

Abstract— In this paper, design and development of interaction cavity for high power and frequency Gyrotron have been carried out for plasma heating during ITER type of experiment start-up. A weakly tapered interaction cavity has been designed to excite $TE_{22,6}$ operating mode at the fundamental harmonic number. The mode selection process and synthesis of interaction cavity have been carried out. Numerical algorithm based electromagnetic simulator MAGIC is used for cold cavity analysis as well as beam-wave interaction computation. The cold cavity analysis for quality factor (Q) value, resonant frequency and mode profile are performed which again confirms the interaction cavity geometry for 120 GHz Gyrotron. The cold characterization of Gyrotron cavity has been carried out using non-destructive method. The interaction cavity is made of high quality oxygen free high thermal conductivity copper (OFHC). Gyrotron interaction cavity of 120 GHz has been experimentally characterized using VNA. In the experiments, quality factor and resonant frequency have been measured.

Index Terms— **Gyrotron, ITER, mode selection, Cold characterization, wall losses**

I. INTRODUCTION

Gyrotron is fast wave microwave tube operating at millimeter and sub-millimeter region of RF spectrum. Gyrotron finds wide applications in the fields of plasma research, THz spectroscopy, atmospheric analysis, material processing etc. Interest in Gyrotron has grown tremendously due to its potential applications in energy generation from fusion energy under global International Thermonuclear Experimental Research (ITER) program. This is necessitated due to Electron Cyclotron Resonance Heating (ECRH) phenomena in plasma caused by high frequency and high power Gyrotron [1]. Interaction cavity is very important component of Gyrotron. The beam-wave interaction takes place in the interaction cavity. Gyrotrons consist of resonant cavity in a strong and continuous magnetic field. A beam of relativistic electrons enter the cavity and interacts with the RF field present in the cavity. In the synthesis of cylindrical cavity, various design equations are used for mode selection, calculations of cavity geometrical parameters, calculation of electron beam current and beam voltage, etc. The operating mode selection is the most important part of Gyrotron designing as the overall performance of the device directly depends on the selected operating mode [2]. The mode selection is carefully studied with the aim of minimizing mode competition and restricting excitation of undesired modes in the cavity as well as to obtain a desired power level. Interaction structure is a very important component of a Gyrotron for RF generation. In the gyrotrons, the beam-wave interaction takes place in the interaction structure, also called as cavity due to its resonant behavior. The simple cylindrical interaction cavity is a three section structure with an input taper, uniform middle section and an output taper. The input taper is a cut-off section, which prevents the propagation of RF power towards the electron gun [3]. The cold cavity analysis and beam wave interaction takes place at the uniform middle section where the RF field exits in the form of standing wave. The output taper section converts the standing wave into the traveling wave. The reducing radius of the input taper section provides higher cut-off frequency region to the signal resonating in the middle section and thus the resonating signal is reflected back. The output taper section is also a tapered cylindrical waveguide of increasing radius. The design of cavity resonator for Gyrotron oscillators requires the knowledge of the RF field profile, resonator eigen frequencies, and the quality factor Q [4].

The synthesis and analysis of interaction cavity have been carried out using in house codes [5]. The parameters such as cavity radius, beam radius, limiting current, voltage depression and wall loss were obtained for different modes. After evaluating above parameters, few higher order modes have been selected. Further on the basis of other parameters like start oscillation current $TE_{22,6}$ is selected as the optimized operating mode. On the basis of the selected operating mode and diffractive quality factor, the interaction cavity geometrical parameters are calculated. The cavity geometry has been modeled, simulated and finally designed using the self-consistent particle-in-cell (PIC) code MAGIC. In this paper a detail design of the interaction cavity of 120GHz Gyrotron is presented. The simulation results show the output power 1MW at the operating frequency 120 GHz. Interaction cavity is quite practical for 1 MW output power at 120 GHz operating frequency due to its easy fabrication.

II. DESIGN OF CAVITY

In this paper design methodology of interaction cavity for high frequency gyrotron has been described. The Gyrotron interaction cavity consisting of three parts, the down-taper (L_1), the middle section (L), and the up-taper (L_2) is shown in Fig. 1, where Y_1 is down-taper angle, Y_3 is up-taper angle and R_c is cavity radius. The electrical design of interaction cavity for 120 GHz, 1MW Gyrotron has been carried out through synthesis and cold cavity analysis, beam-wave interaction analysis and parametric analysis, etc. Synthesis of interaction cavity is basically getting first hand information regarding operating mode profile in the cavity, study of operating mode related to space charge, quality factor, wall loss, start oscillation current, etc. leading to selection of a proper operating mode. Particle-in-cell (PIC) electromagnetic simulation code MAGIC [6] is used for beam-wave interaction analysis and parametric analysis.

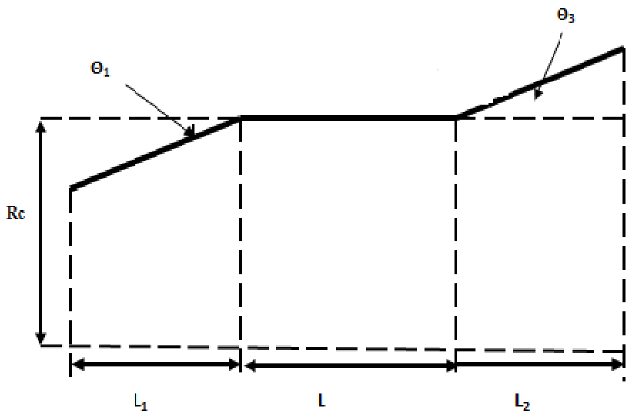

Fig. 1: Schematic diagram of cavity [3]

Table 1 shows the design parameters for 120 GHz Gyrotron cavity. The cold cavity analysis is carried out to verify the oscillation of desired operating mode and axial electric field profile in cold condition. The final design goal of any gyrotron interaction cavity is its output power and frequency performance according to the requirement and thus small changes in the geometrical parameters can be made during beam-wave interaction simulations for the optimization of output power. The completely closed interaction cavity except the output taper mouth is made of fully conducting wall for the beam-wave interaction simulations in MAGIC. Fig. 2 clearly shows the required profile as a Gaussian profile with the peak electric field value at the center of the middle section. Fig. 3 shows the meshed interaction cavity with gyrating electron beam. The asymmetric mode $TE_{22,6}$ is selected as the operating mode for 120 GHz, 1 MW Gyrotron after going through different mode selection process. The device can generate several MW's of electromagnetic power by the efficient interaction of the gyrating electron beam of very high electron beam power with RF in the interaction cavity. A cylindrical interaction cavity is quite practical for 1 MW output power at 120 GHz operating frequency due to its easy fabrication and thus used for the design. Table 2 shows the optimized interaction cavity geometry for 120 GHz Gyrotron. MAGIC code has been used for analyzing the asymmetric $TE_{22,6}$ mode and beam wave interaction. An electron beam posses all the desire beam properties has been launched at the first radial maxima of the input taper entrance for beam wave interaction simulation. The same beam interacts with normalized RF field profile while propagate across the cavity and terminates on the other end wall. The code is run using the Maxwell CENTERED algorithm at confined magnetic field.

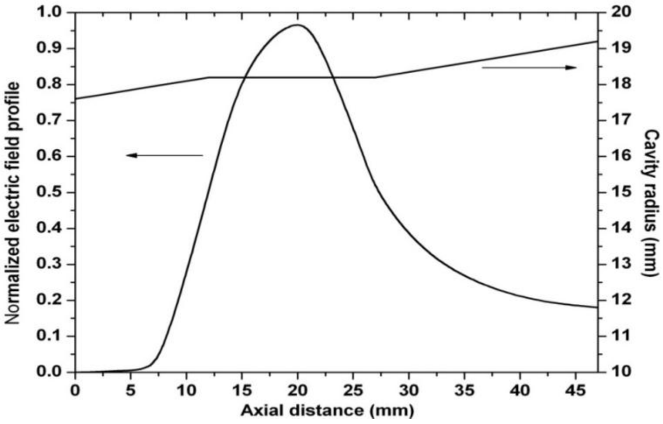

Fig. 2: Normalized axial electric field profile

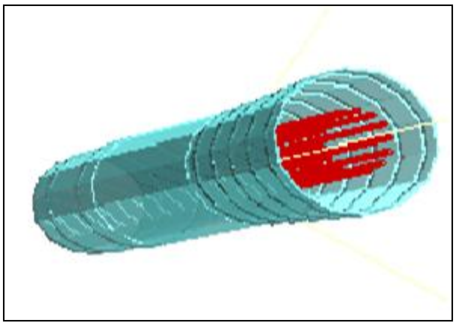

Fig. 3: View of interaction cavity with meshing in MAGIC [6]

Table 1: The design parameters of the 120 GHz Gyrotron [4]

Parameter	Value
Frequency (f_o)	120 GHz
Output power (P_o)	$\geq$ 1.0 MW
Efficiency (η)	$\geq$ 30%
Beam voltage (V_b)	80 kV
Beam current (I_b)	40 A
Alpha (α)	1.5
Magnetic field (B_0)	4.82 T

The electron beam emitted from the magnetron injection gun (MIG) is launched at the input taper entrance. The electron beam properties like beam radius, larmor radius and velocity ratio are defined at the input taper section entrance. The same electron beam moves across the interaction cavity and interacts with insignificant electric field of operating mode in middle section. The bunching process takes place in gyrating electron beam due to the relativistic effect and a coherent radiation emission mechanism starts in the electrons, which amplifies the weak operating mode signal in the resonant cavity. Fig. 4 shows the phase space diagram of the particles energy, which indicates the efficient interaction as the density of the low energy particles increases along the cavity length. The maximum energy of the electrons is transferred to the rf at the cavity center. From the frequency spectrum shown in Fig. 5, it is clear that the frequency of 120.24 GHz is excited with maximum gain. Fig. 6 shows output power profile with respect to time, achieving the steady state after 100 ns of the start operation. The simulated results show that the output power is 1.65 MW at confined magnetic field of 4.82 T, beam voltage 80 kV and beam current 40A. The interaction efficiency is more than 35%.The sensitivity analysis gives the flexibility in actual fabrication of the device and establishes a range of cavity geometrical and electron beam parameters. The sensitivity analysis always helps in the optimization of design as well as decision of tolerance limits of the parameters of the device.

Table 2: Optimized cavity geometry of 120 GHz Gyrotron

Parameter	**Value**
Middle section length (L)	15 mm
Input taper length (L_1)	12 mm
Output taper length (L_2)	20 mm
Cavity radius (R_c)	18.1 mm
Input taper angle (θ_1)	2.8°
Output taper angle (θ_3)	2.8°
Quality factor (Q)	706

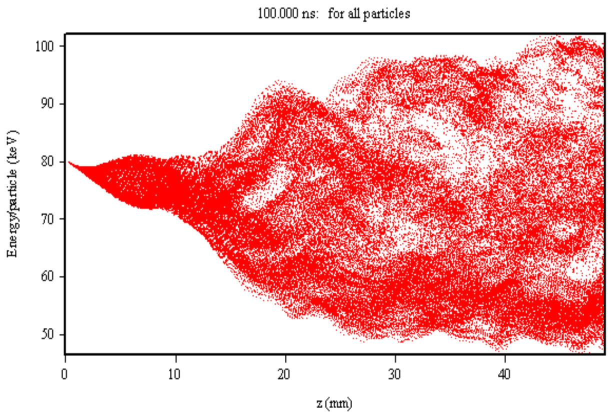

Fig. 4: Phase space diagram of the emitted particles

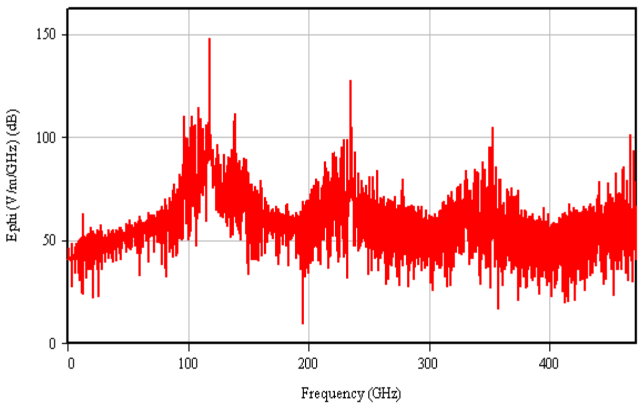

Fig. 5: Frequency spectrum for the $TE_{22,6}$ mode gyrotron

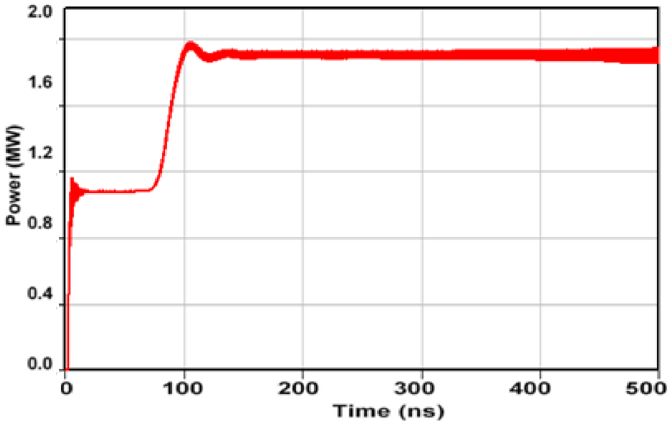

Fig. 6: Output power with respect to time for gyrotron operates at $TE_{22,6}$

III. DEVELOPMENT OF CAVITY

Cylindrical interaction cavity has been fabricated for 120 GHz Gyrotron. The interaction cavity is made of high quality oxygen free high thermal conductivity copper (OFHC) due to its excellent electrical properties, but due to some finite resistivity, some losses occur in the electromagnetic power in the form of ohmic heating. The cold characterization of the 120 GHz Gyrotron cavity has been carried out. The fabrication of cavity with oxygen free high conductive (OFHC) copper material has been performed. Considering the available computerized numerical controlled (CNC) machine and standard boring tool, cavity has been fabricated. Machined surface and angle have been scanned with co-ordinate measuring machine (CMM). Surface roughness of the cavity has been measured using surface profiler. The achieved surface finish of the cavity was 0.4 micron, Fig. 7 shows fabricated cavity for 120 GHz Gyrotron. Nondestructive horn antenna method has been used for the resonance frequency and total quality factor measurement [7]. The interaction cavity is placed at 45^0 with respect to both antennas as shown in Fig.8. In the experiment, the bigger mouth of the resonator cavity is exposed in the RF, so that at the resonance, the power will be coupled into the resonator resulting less power reflected from the plane at the mouth of the resonator. The resonator is so aligned and oriented so that a peak or null of the resonator mode is detected with a receiver properly. The eigen frequency and *Q* are measured by the resonance curve displayed on the Vector Network Analyzer [8]. The measurement is performed in far field region of antenna field to avoid any disturbance. This reflected signal shows resonating behavior of interaction cavity at a particular frequency. Fig. 9 shows the sharp peak of reflected signal at 119.5 GHz. The measured frequency is 119.5 GHz, which is within the design constraint, that is, 120 GHz ±0.5 GHz. Further, with the help of the resonating curve shown in Fig. 9, the *Q* value is calculated by 3 dB method and bandwidth is 150 MHz [9]. In the experiments, quality factor and resonant frequency are measured. Table 3 shows the comparison between calculated and measured values of quality factor and resonant frequency.

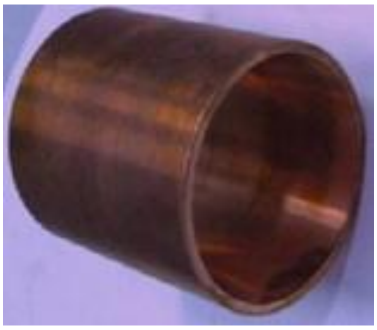

Fig. 7: Fabricated interaction cavity for 120 GHz Gyrotron

Table 3: Comparison values of resonate frequency and quality factor

Calculated	**Measured**	**Calculated**	**Measured**
f (GHz)	f (GHz)	Q	Q
120.05	119.5	706	702

Fig. 8: Cold test set up of high frequency gyrotron cavity [8]

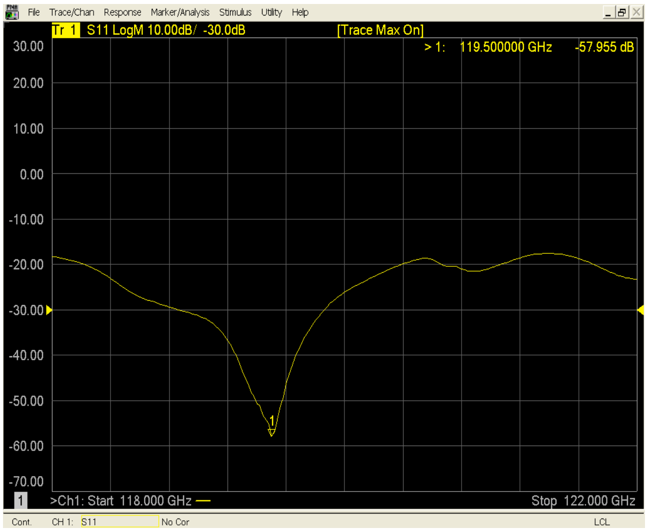

Fig. 9: Resonance curve of 120 GHz cavity using VNA [8]

IV. CONCLUSION

The design methodology of interaction cavity has been developed for high power Gyrotron. The selected operating mode shows small mode competition and small wall losses. To check the stability of the operating mode, eigen mode and cold cavity analysis have been carried out. The beam-wave interaction computation shows more than 1MW of output power at 120 GHz of operating frequency for the designed interaction cavity. Thus, the presented design of a 120 GHz Gyrotron interaction cavity clearly shows the feasibility of 1 MW of output power growth when operating with the $TE_{22,6}$ mode. Thorough sensitivity analyses of each of the electron beam parameters and cavity geometry are also carried out. On the basis of design value, a test interaction cavity has been fabricated. The RF measurement has been carried out for 120 GHz Gyrotron interaction cavity. Non-destructive horn antenna method also called as non-destructive external adapter method is used for the measurements of resonant frequency and Q value. The experimental results show the good agreement between measured and simulated results.

ACKNOWLEDGMENT

This work was carried out under a CSIR Network project. The authors are thankful to the Director, CSIR-CEERI, Pilani and all other project team members for their support.

REFERENCES

[1] C. J. Edgecombe, Gyroton Oscillators: Their principles and practice. London (UK) Taylor & Francis Ltd., 1993.

[2] G. S. Nusinovich, Introduction to the physics of Gyroton, Maryland, JHU, USA, 2004.

[3] M.V. Kartikeyan, E. Borie and M Thumm, Gyrotron: High power microwave and millimeter wave technology. Berlin Heidelberg, springer-verlag, 2003.

[4] M.K. Alaria, P. Mukerjee, S. Das and A.K. Sinha, "Study of Cavity and Output Window for High Power Gyrotron", Journal of fusion Energy, Vol. 30, No 1, February, 2011

[5] N. Kumar, U. Singh, A. Kumar, H. Khatun, A.K. Sinha, "Numerical design of 120 GHz, 1 MW gyrotron interaction cavity", Infrared Physics and Technology, vol. 54, pp. 512, 2011

[6] MAGIC User Manual: 2007 Version of Magic 3D, ATK Mission Research

[7] V.Yadav, S.Sharan, N. Kumar, M.K. Alaria, B. Jha, SC Deorani, AK Sinha and PK Jain, "Cold characterization of cylindrical open resonator for Gyrotron", Infrared Physics and Technology Vol.54, No.4, PP 337-342, July 2011

[8] Agilent 85070E Vector Network Analyzer (VNA)

[9] H.O Prinz, A Arnold , K Koppenburg , M Thumm, Development of a broadband real-time frequency measurement system for high power mm-wave gyrotrons, GeMiC 2005, pp 41-44, April 5-7, 2005.

AUTHOR BIOGRAPHY

MK Alaria was born in Pilani, India. He received the M.Tech degree from Delhi University, India, in 2003. He received the Ph.D. degree from DAVV, Indore, India in 2015. He is currently a scientist in Gyrotron Lab, Microwave Tubes Area, Central Electronics Engineering Research Institute (Council of Scientific and Industrial Research) Pilani, Rajasthan, India. His major field of research is Microwave Tubes, MW applications, and mathematical modeling and simulation, in general, and TWT and gyro-devices, in particular. He has authored/coauthored more than 60 research papers in peer-reviewed journals and conferences. He is a member of IETE and VEDA Society.

Y Choyal received M.Sc. in 1991 from DAVV, Indore. He obtained Ph.D. degree in 1996, his doctoral work on high power microwave generation. He continued in the department first as a research associate from 1996 to 1997 and then as a lecturer in National laser program till July 2000. At present he is a senior lecturer in Dept. of Physics DAVV, Indore. He was awarded Japanese Society for the promotion of Science (JSPS) fellowship and worked at Niigata University, Japan during 2001 to 2003. Presently, he is working on Cherenkov and Cyclotron devices and theoretical investigations on interaction of relativistic electron beam with flue gases.

AK Sinha was born in Bhabua, India, in 1954. He received the Ph.D. degree from Ranchi University, Ranchi, India, in 1986. He is currently a senior scientist in Microwave Tube Area, Central Electronics Engineering Research Institute (Council of Scientific and Industrial Research) Pilani, Rajasthan, India, where he is currently leading the Gyrotron activity. He visited the Lancaster University, Lancaster UK, Seoul National University, Korea, Massachusetts Institute of Technology, Cambridge and Karlsruhe Institute of Technology, Karlsruhe, Germany, under various schemes. He has authored/co-authored more than 200 research papers in peer-reviewed journals and conference proceedings. His major field of research includes megawatt tubes, megawatt applications, and mathematical modeling in general and TWT and gyro devices in particular. He is a member of IETE, IPA, ISCA, IFTA, IVS, CSI, PSI and VEDA Society.