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Effect of cavity geometry on the performance of a gyrotron

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HIGHLIGHTS

- Numerical analysis of gyrotron cavity geometry effect on Q value, ohmic wall heating and field profile.
- Experimental analysis of gyrotron cavity geometry effect on Q value, ohmic wall heating and field profile.
- Effect of gyrotron cavity geometrical parameters on the start oscillation current.
- Effect of gyrotron cavity geometrical parameters on the beam–wave interaction efficiency.

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ABSTRACT

The effect of interaction cavity geometry on the gyrotron performance in terms of cold cavity parameters (*Q* value and axial electric field profile), Ohmic wall loss, start oscillation current and interaction efficiency are analyzed in detail in this article. The measurement of *Q* value and axial electric field profile is also performed for the cavities with different geometries by using non-destructive and perturbation techniques, respectively. Scattering matrix code is used for the computation of *Q* value and axial electric field profile and results are compared with the experimental data. A Particle-in-Cell code and a specific beam–wave interaction computation code based on generalized non-linear theory are used in the efficiency calculations. For all numerical and experimental analyses, the case of 42 GHz, 200 kW gyrotron is considered here.

1. Introduction

Gyrotron is a vacuum based device used as a high power radiation source in millimeter and sub-terahertz region of electromagnetic wave spectrum. The device was invented in the decade of 1965 due to the requirement of a high power millimeter wave source in plasma fusion. At present gyrotron is a key device in several scientific and industrial applications such as plasma fusion, NMR spectroscopy, industrial heating, ADS system, [1,2]. Since the time invention of gyrotron, substantial research work has been carried out theoretically as well as technologically to enhance the power, frequency and efficiency of the device [3–5]. Record power generation (∼1 MW CW at 170 GHz frequency) and record frequency generation (∼1 THz) from gyrotron has been reported in Refs. [6–8]. The gyrotron with a magnetron injection gun and a simple cylindrical open resonator cavity is used in most of the cases from low power, low frequency to high power, high frequency. To enhance the power, frequency and efficiency of gyrotron, the research on different kind of gyrotrons such as large orbit gyrotron, coaxial cavity gyrotron, sheath beam gyrotron, double beam gyrotron, is also going on in various research institutes [9–12].

The perfect design of resonator cavity is an important issue in gyrotron as the beam–wave interaction takes place in the resonator cavity and the geometrical parameters of cavity contribute a decisive role in the efficient operation of the device. In this article a detail analysis of the effect of cavity geometrical parameters on the *Q* value, cavity wall heating, mode competition and beam-wave interaction efficiency are analyzed in detail. The case of 42 GHz, 200 kW gyrotron is considered for the experimental and numerical analysis of the resonator cavity. This gyrotron is under development for the electron cyclotron resonance heating in Indian tokamak system ADITYA. Some basic design parameters and goals for this gyrotron are summarized in Table 1. The in-house developed as well as commercially available design codes are used for the analysis and described in the related sections. The experimental method for the measurement of *Q* value and the axial electric field profile is also discussed. The complete manuscript is divided into five sections including introduction. In Section 2, the experimental and numerical results of the effect of cavity geometrical parameters on *Q* value, Ohmic wall loading and axial electric field profile are discussed. In Section 3, the start oscillation current and relation with cavity geometrical parameters is discussed. Section 4 de-

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Table 1
Design specifications and goals for 42 GHz gyrotron.

Frequency	42 GHz
Power	200 kW
Efficiency	>30%
Beam current	8–12 A
Beam voltage	62–67 kV
Operating mode	TE_{03}
Diffractive Q	700–1200
Ohmic wall heating (at room temp.)	<1 kW/cm^2

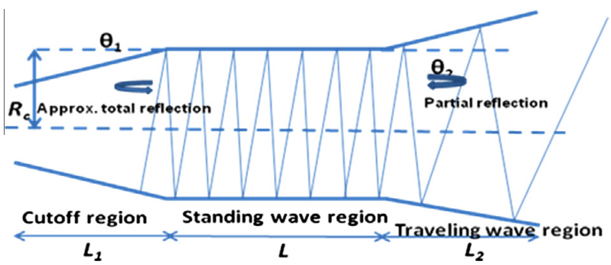

Fig. 1. A schematic view of interaction cavity.

scribes the beam–wave interaction efficiency with cavity parameters. For the calculation of beam–wave interaction efficiency, commercially available Particle-in-Cell code and in-house developed non-linear code are used and thus the generalized non-linear theory for gyrotron is also discussed in brief in Section 4. The results are summarized in the last section.

2. Experimental and numerical analysis of cavity geometry effect on Q value, ohmic wall heating and field profile

Fig. 1 shows a schematic view of simple cylindrical interaction cavity. This kind of cavity consists of three sections, namely input taper section (cutoff region), middle section or standing wave region and output taper section (traveling wave region). The cutoff region is a down tapered cylindrical wave guide shows approximately complete reflection of the RF. The traveling wave region is an up tapered wave guide, which behaves like a horn antenna for the middle section and the generated RF power travels through this region. Partial reflection of RF also occurs at the output taper section due to the geometrical mismatching, which is essential for the formation of standing wave in middle section with high Q value. The formation of standing wave in the middle section is necessary for the high efficiency beam–wave interaction. The output taper angle and middle section length are critical geometrical parameters in the optimization of Q value. A higher Q enhances the ohmic wall loading at the middle section which further reduces the net efficiency of the device and create thermal issues in the cavity. On the other hand a lower Q value also affects the process of electron beam bunching and thus reduces the beam–wave interaction efficiency. In case of the interaction cavity as shown in Fig. 1, the Q value can be determined in terms of diffractive Q (Q_{diff}) and ohmic Q (Q_{ohm}). The diffractive Q determines the power loss due to the RF propagation through the output taper section and similarly ohmic Q exhibits the power loss in the middle section due to the thermal conductivity of cavity material (also called ohmic wall loss) [13].

The numerical as well as experimental analyses are performed to analyze the Q value and axial electric field profile with respect to the cavity geometry. The interaction cavity is simulated by using the scattering matrix numerical code Cascade [14]. This ohmic wall loss for smooth copper at room temperature is calculated by using the expression given in Eq. (1) [13]. Electrical properties of OFHC copper is used in the calculation of this ohmic wall loss for smooth copper at room temperature. Technically, the ohmic wall loss must be below 1 kW/cm^2 and this constraint is used in the design of interaction cavity and to determine the Q value. For the measurements of Q value and axial electric field profile, several cavities were fabricated with different down taper angle, middle section length and up taper angle. The Gaussian type of axial electric field profile is required in the interaction cavity to keep the ohmic wall loss minimum and beam–wave interaction efficiency maximum [13,15]. The experimental method called non-destructive method is used for the measurement of Q value for different geometries of interaction cavity [16–20]. Fig. 2a shows a schematic view of the measurement setup for Q value. Two pyramidal WR22 horn antennas are used to launch and receive the plane wave in far field region. Both horn antennas are connected with Agilent Performance Network Analyzer (PNA) (frequency range: 200 MHz to 50 GHz). In the experiment, the bigger mouth of the resonator is exposed in the RF, so that at the resonance, the power will be coupled into the cavity resulting less power reflected from the plane at the mouth of the cavity (Fig. 2a). The resonance curves display on the PNA screen from where the Q value can be measured by using −3 dB method. Fig. 2b shows the experimental setup for the measurement of axial electric field profile. The technique used for the experimental determination of axial electric field profile is referred

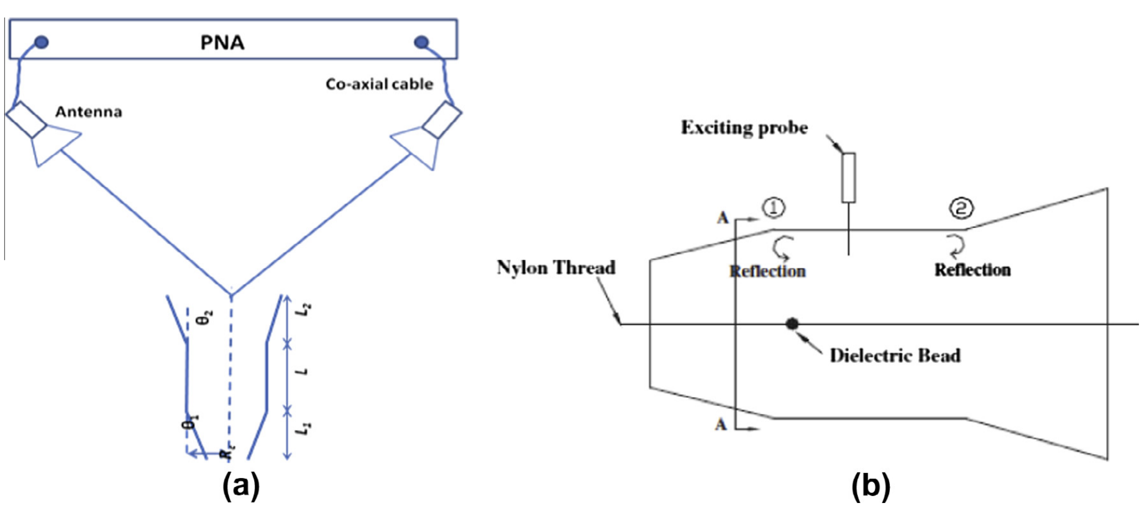

Fig. 2. (a) A schematic view of experimental setup for the measurement of Q value, and (b) Schematic view of experimental set up for the measurement of axial field profile.