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ORIGINAL RESEARCH

Improved Design of Beam Tunnel for 42 GHz Gyrotron

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Abstract In gyrotron, there is the chance of generation and excitation of unwanted RF modes (parasite oscillations). These modes may interact with electron beam and consequently degrade the beam quality. This paper presents the improved design of the beam tunnel to reduce the parasite oscillations and the effect of beam tunnel geometry on the electron beam parameters. The design optimization of the beam tunnel has been done with the help of 3-D simulation software CST-Microwave Studio and the effect of beam tunnel geometry on the electron beam parameters has been analyzed by EGUN code.

Keywords Magnetron injection gun · Gyrotron · Electron gun · Plasma heating · Beam tunnel

Introduction

Gyrotron is a high power, high frequency microwave device which produce coherent millimeter and sub-millimeter radiation [1]. The gyrotron is the only RF source used in the electron cyclotron resonance heating (ECRH) for fusion plasma in the various TOKAMAK systems [2]. A 42 GHz 200 kW continuous wave output power gyrotron is being developed for the electron cyclotron resonance plasma heating for the Indian TOKAMAK system [3]. The basic specifications of the gyrotron are given in Table 1. The triode type Magnetron injection gun (MIG) with a modulating anode and an accelerating anode has been designed [4]. Here as beam tunnel the part of the drift section between the MIG gun and the cavity is considered which is occupied with a highly lossy structure. Approximately 3–5% of generated RF power in cavity can reach the MIG [5]. This amount of RF power is sufficient to degrade the beam quality and even can damage the MIG cathode. The beam tunnel is mainly used to prevent the propagation of generated RF power from the cavity to the MIG. Lossy ceramics are used in the beam tunnel to absorb the RF power and to avoid the excitation of the parasitic modes. In the previous reported work, the design of the beam tunnel for the 42 GHz, 200 kW gyrotron has been presented (Fig. 1). In the simulation, the absorption, the reflection and the transmission of RF power by the beam tunnel have been analyzed. The systematic approach for the analysis of the parasitic oscillation excitation has also been reported [6]. Four different approaches, the Q value study, the mode maxima-electron beam radius mismatching, the electron cyclotron frequency mode excitation frequency mismatching and the backward wave interaction analysis have been used for the parasitic oscillation analysis. To finalize the design of beam tunnel, the computer simulation has been carried out for the absorption, the transmission and the reflection of the RF power by the beam tunnel for the different lossy ceramic materials. The analysis for the Q value for different ceramic materials has also been performed. As the anode of the MIG can also act as cavity, and thus there is also the chance of generation

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Table 1 Basic specifications of 42 GHz gyrotron

Operating mode	TE_{03}
Operating frequency (f_0)	42 GHz
Beam voltage (V_0)	65 kV
Beam current (I_0)	10A
Output power (P_0)	200 kW
Efficiency (η)	33%

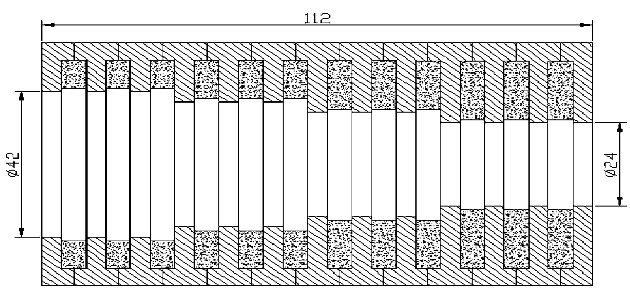

Fig. 1 A schematic of beam tunnel with input diameter, output diameter and length (all dimensions are in mm)

of excitation of unwanted RF modes. The excitation of the parasitic oscillations in the millimeter wave gyrotrons is a concerning problem for the output power and the efficiency [7]. The excitation of these waves leads to electron energy spread that spoils the beam quality and, hence, degrades the gyrotron efficiency [8]. The goal of the beam tunnel design is to avoid the parasitic oscillations as much as possible. The length of the main anode can be reduced by increasing the length of the beam tunnel to minimize the rf excitations [9]. For this purpose, the beam tunnel design has been modified. Here, the aim to modify the design of beam tunnel was to minimize the rf excitation toward the electron gun side. The study of the beam tunnel length and its effect on the electron beam parameters like transverse to axial velocity ratio of electron beam (α) and transverse velocity spread ($\delta v_\perp$) has been carried out by using electron trajectory program EGUN [10]. Then, the design optimization of the modified beam tunnel has been finalized with the help of 3-D simulation software CST-Microwave Studio [11].

Effect of Beam Tunnel Geometry on Electron Beam Parameters

The beam tunnel provides the path for the gyrating electron beam from the magnetron injection gun (MIG) to the interaction cavity. Table 2 shows the optimized parameters of MIG parameters indicating the length of the beam tunnel. The magnetic field is strongly inhomogeneous in the

Table 2 Different optimized parameters of MIG (indicating the length of beam tunnel)

Cathode radius	22.6 mm
Slant length of emitting surface	7.0 mm
Slope angle of cathode	28 degree
Beam current	10.3 A
Beam voltage	65 kV
Modulating anode voltage	29 kV
Magnetic field at interaction region	1.65 Tesla
Maximum transverse velocity spread (%)	2.65
Transverse to axial velocity ration of electron beam (α)	1.26
Length of beam tunnel	112 mm

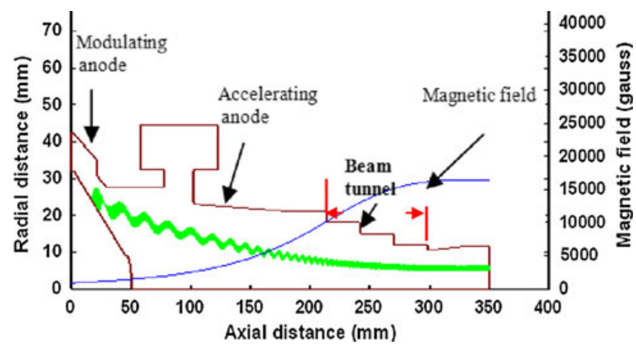

Fig. 2 MIG geometry with beam tunnel and beam profile

beam tunnel so that the gyrating electron beams are compressed sufficiently to achieve the required beam parameters for the interaction in the cavity. Due to the highly lossy ceramic rings used in the beam tunnel and inhomogeneous magnetic field, various kinds of beam instabilities occur in the electron beam [12].

To characterize the quality of electron beam, maximum transverse velocity spread of the electron beam ($\delta\beta_{\perp max}$) is used. To see the effect of the beam tunnel length on the electron beam parameters like transverse to axial velocity ratio of electron beam (α) and the maximum transverse velocity spread ($\delta\beta_{\perp max}$), the length of the beam tunnel has been varied in steps. As shown in Figs. 2, 3 the drift section between the MIG geometry and the cavity is equipped with two beam tunnels of different length.

Figure 4 shows the variation of transverse to axial velocity ratio of the electron beam (α) with the change in the beam tunnel length. The value of the velocity ratio increases with increase in the beam tunnel length. Figure 5 shows the variation of the velocity spread with the change in the beam tunnel length. The value of maximum transverse velocity spread (%) decreases with increase in the beam tunnel length. From Figs. 4, 5 it is clear that with increase in the length of the beam tunnel the quality of the electron beam is improved. Table 3 shows the initial and modified dimensions of the beam tunnel.

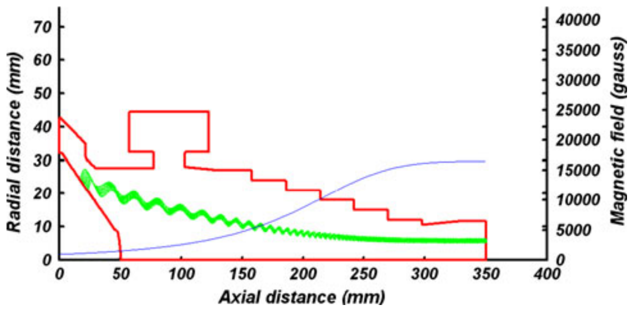

Fig. 3 MIG geometry with modified beam tunnel and beam profile

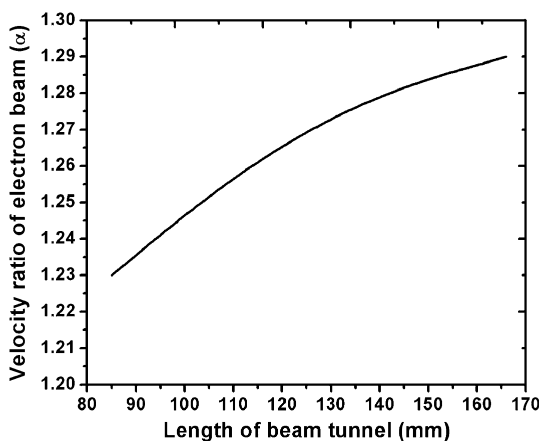

Fig. 4 Variation of velocity ratio of electron beam with beam tunnel length

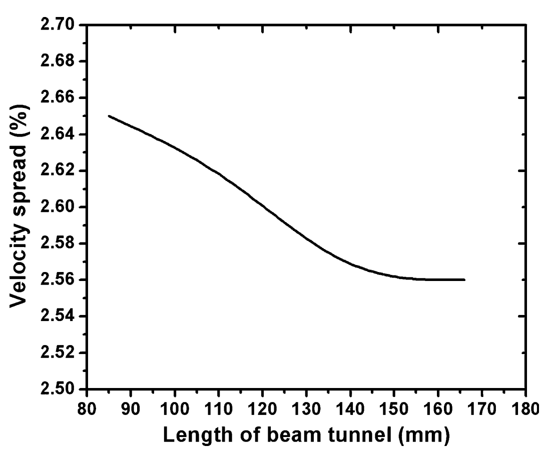

Fig. 5 Variation of maximum transverse velocity spread of electron beam with beam tunnel length

Table 3 Initial and modified dimensions of the beam tunnel

Parameters	Initial (mm)	Modified (mm)
Beam tunnel length	112	166
Beam tunnel inner diameter towards cavity side	24	24
Beam tunnel inner diameter towards MIG side	42	54

Modified Design of Beam Tunnel

Based on the modified dimensions of beam tunnel (Fig. 6), the commercially available 3-D simulation codes CST-Microwave Studio (CST-MS) has been used for the analysis of RF absorption and transmission by the beam tunnel. The lossy ceramic AlN-SiC (Loss Tangent (Tanδ) = 0.25, Relative Permittivity (ε_r) = 15, Composition = 40 wt%SiC) has been used for the computer simulation.

The thickness of the lossy ceramic rings has been optimized on the basis of maximum RF absorption by the beam tunnel. Figure 7 shows the simulation results of RF absorption coefficient (A), transmission coefficient (T) and reflection coefficient (R) for AlN-SiC obtained by commercially available simulation codes CST-MS.

In the simulation results, the optimized thickness of the ceramic rings and the copper rings has been considered as 5 and 4 mm, respectively. Figure 7 clearly shows that, approximately 92% of RF power entered in beam tunnel has been absorbed. Further, there is approximately no RF power transmitted towards the MIG. Due to some impedance mismatching inside the beam tunnel approximately 10–12% of RF power is reflected back.

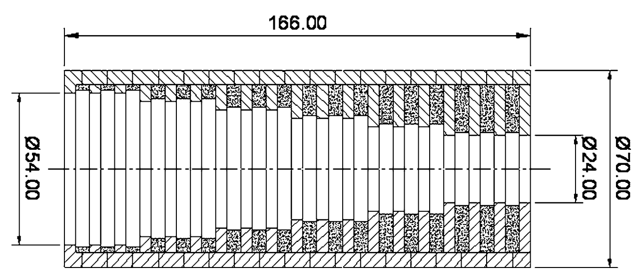

Fig. 6 The modified view of beam tunnel with input diameter, output diameter and length (all dimensions are in mm)

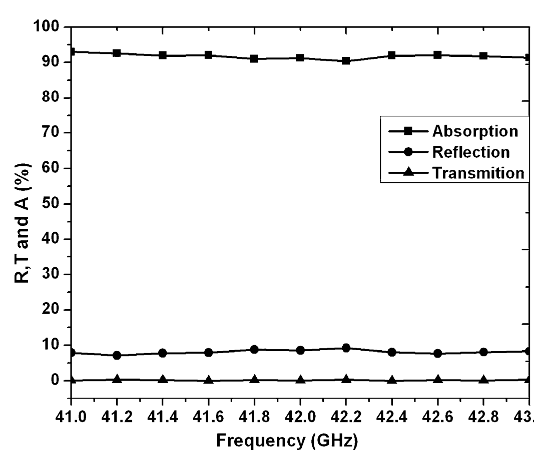

Fig. 7 Reflection (R), absorption (A) and transmission (T) coefficient versus frequency for AlN-SiC

Q Value Study of Parasitic Oscillation

The concern in the beam tunnel design is that no beam wave interaction takes place, so the beam current should not exceed the start oscillation current in the beam tunnel. The starting current for the excitation of a particular mode depends inversely on the Q value [13]. The beam tunnel is a highly discontinuous structure due to the lossy ceramic rings placed alternatively after each copper ring. So inside the copper rings, the reflection at the ring edges occurs and the standing wave formation take place. To suppress the start up of any mode inside the beam tunnel, the Q value should be as small as possible. The Q value of the beam tunnel has been obtained by the eigenmode simulation at gyrotron operating frequency. For the pure metallic beam tunnel the simulated Q value is around 16,000. The simulated Q value for AlN-SiC lossy ceramic used in the beam tunnel is 216. The Q value of the ceramic embedded beam tunnel is very small compare to the pure copper beam tunnel. So the chance of the parasitic mode oscillations excitation in the beam tunnel reduces several folds.

Conclusion

The improved design of the beam tunnel for the 42 GHz, 200 kW gyrotron has been presented. The length of the main anode of MIG has been reduced by increasing the length of the beam tunnel to minimize the rf excitations towards the MIG side. The study of the beam tunnel length and its effect on the electron beam parameters has been carried out. The value of velocity ratio (α) increases and the value of maximum transverse velocity spread (%) decreases with increase in beam tunnel length. The simulation of the Q value has also been performed to analyze the parasitic mode oscillation. The results show that the parasitic oscillations in the designed beam tunnel are completely suppressed. Compared with the first 42 GHz beam tunnel, the modified beam tunnel is also expected that, the parasitic oscillations are not exciting in the beam tunnel.

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