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TRIODE MAGNETRON INJECTION GUN FOR 132 GHz GYROTRON FOR 200 MHz DNP-NMR APPLICATION

Nitin Kumar*, Udaybir Singh, and Ashok K. Sinha

Gyrotron Laboratory, MWT Area, CSIR-Central Electronics Engineering Research Institute, Pilani 333031, India

Abstract—A 132 GHz gyrotron, operating at fundamental harmonic, is designed for the 200 MHz DNP-NMR experiment. In this article, the design of high quality electron beam source is presented. 2.5 dimensional code EGUN and 3 dimensional code CST-Particle Studio are used in the design and optimization of electron gun. The design of electron beam source is performed for a band of magnetic field values at the emitter surface and cavity center which is necessary for the frequency tunabilty of 2–3 GHz needed in DNP/NMR experiments. The results confirm the axial and transverse velocity spreads around 1% and 2.2% and a pitch factor of 1.5. The parametric analyses are also performed for the various electrical parameters such as emitter voltage, anode voltage, emitter magnetic field, etc..

1. INTRODUCTION

Gyrotrons have been established as efficient sources of high power in millimeter wave and THz wave bands [1, 2]. The device is based on the phenomena of cyclotron resonance maser instability and was invented in the decade of 1960 for the heating of magnetically confined plasma [3, 4]. The gyrotron exhibits several unique features [5] in support of high power generation in millimeter wave and THz wave bands and thus the device is used in several scientific and technological applications such as plasma heating, plasma diagnosis, spectroscopy, security, material treatments, etc. [6, 7]. Since last one decade, huge efforts are made by researchers todevelop the sub-THz and THz gyrotrons specifically for the application of NMR (Nuclear Magnetic Resonance) spectroscopy [8, 9]. The sub-THz/THz gyrotronsare used to pump tens of watt RF power at a particular frequency (decided by

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* Corresponding author: Nitin Kumar (nitingkv@gmail.com).

the proton frequency in NMR) into the NMR spectroscopic system to enhance the sensitivity of experiments via a technique called Dynamic Nuclear Polarization (DNP). The sub-THz/THz gyrotrons at different frequencies has been developed at MIT, USA, University of Fukui, IAP Russia, etc. for different proton frequency NMR systems and the present development status of DNP gyrotrons isgiven in Refs. [8, 9]. The main design and technological challenges for such gyrotrons are the superconducting magnet system of very high magnetic field value, frequency tunability of few GHz (generally from 2–5 GHz) and highly stable operation of the device [8, 10, 11]. These technological features of DNP gyrotrons make the design and development of the device slightly different from high power fusion gyrotrons [2, 6, 8, 9].

30–50 watt RF power at 132 GHz frequency is required for dynamic nuclear polarization in 200 MHz NMR spectrometer. Considering this requirement, the development of gyrotron as RF source of 132 GHz frequency for 200 MHz DNP/NMR experiment is started. The basic specifications of this gyrotron are summarized in Table 1. To obtain the smooth frequency tuning of 2–3 GHz, a series of cavity axial modes is excited during the beam wave interaction in the interaction cavity [8]. In this process the magnetic field values at cavity center and emitter are changed continuously. The DNP gyrotrons must perform continuously with very high stability in output power and frequency for very long operating time (tens of hours). Considering the frequency tunability and highly stable operation of the device, a high quality helical electron beam is needed for the smooth and efficient operation of the device. The helical electron beam must exhibits its quality (velocity spread $< 4\%$ and pitch factor ~ 1.5) in a wide range of magnetic field values to support the frequency tuning with highly stable operation for long time. Considering all these requirements, the design work of electron beam source is presented in this article. The triode type magnetron injection gun (MIG) is considered for the design in place of diode type due to its better control on electron beam parameters. Fig. 1 shows a schematic view of triode type magnetron injection gun.

Table 1. Basic specifications of DNP/NMR gyrotron.

Power	30–50 Watt
Frequency	132 GHz
Frequency tunability	2–3 GHz
Beam voltage	8–12 kV
Beam current	40–60 mA

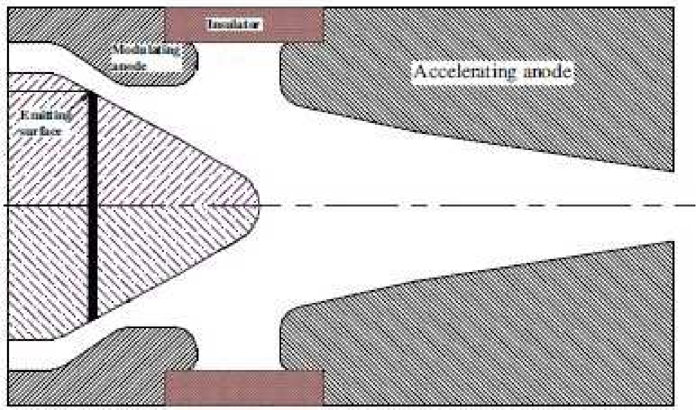


Figure 1. Schematic view of triode type magnetron injection gun.

2. ESTIMATION OF MAGNETIC FIELD PROFILE

Numerical calculations of interaction cavity for 132 GHz gyrotron establish the cavity magnetic field of 4.82 T considering the maximum interaction efficiency. Magnetic field profile of Gaussian type is employed in the gyrotron device with the peak value at the center of interaction cavity (4.82 T). In such type of magnetic field profile, the helical electron beam (HEB) is continuously suppressed adiabatically (p^2/B_0 = constant, p and B_0 are the transverse momentum of gyrating electron and the magnetic field, respectively) and a major fraction of the beam kinetic energy transferred to the transverse component of electrons velocity [12, 13]. The quality of HEB, such as spread in transverse and axial velocities, an optimum value of pitch factor, α (ratio of transverse to axial velocity), highly depends on the magnetic field profile. A rigorous optimization process is carried out to finalize the magnetic field profile considering the minimum velocity spreads and $\alpha \sim 1.5$. Fig. 2 shows the optimized magnetic field profile with the position of interaction cavity center and emitter center. Finite differential method based electron trajectory code EGUN [14] is used in the optimization of field profile and emitter position. Several magnetic field profiles are analyzed for the cavity magnetic fields ranging from 4.8 T to 4.87 T which are required for the frequency tunability of 2–3 GHz. The effect of varying magnetic field profiles on beam quality parameters (spreads and pitch factor) is discussed in Section 5. The numerical design of triode type MIG is performed for the magnetic field profile shown in Fig. 2 and discussed in next section. The distance between cathode to cavity center is optimized as 273.8 mm.

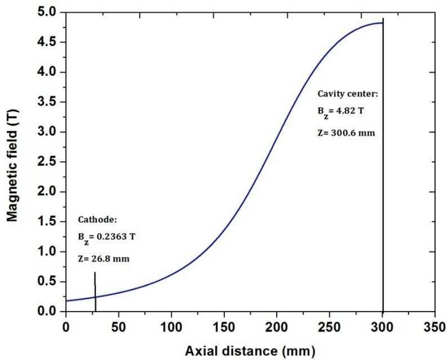


Figure 2. The magnetic field profile with the positions of emitter and cavity center.

3. NUMERICAL DESIGN

The numerical design of 132 GHz MIG is performed by 2.5 dimensional code EGUN. The electron beam launching position at the cavity center is selected at first radial maxima of the operating mode TE_{03} (0.6 mm), which provides maximum coupling of the electron beam with the operating mode. The input parameters for the MIG design such as beam voltage, beam current and cavity magnetic field are given in Table 2. The initial geometrical parameters such as emitter radius, emitterslant angle, emitterslant length, etc. are calculated by using the code MIGSYN [15] based on the theory derived by Baird and Lawson [16, 17]. Based on the calculated geometrical parameters, an initial geometry of MIG is made in EGUN with the magnetic field profile given in Fig. 2. The numerical simulations were performed to optimize the electrodes geometry for high quality helical electron beam. The emitter is simulated in the temperature limited regime in which the total current or the current density was specified. Various technical and theoretical aspects, given in Ref. [18], are considered in the emitter

Table 2. Input parameters for MIG design.

Beam voltage	10 kV
Modulating anode voltage	4 kV
Beam current	50 mA
Cavity magnetic field	4.82 T
Beam radius	0.6 mm

design to minimize the velocity and pitch factor spreads. The applied current is carried out by 18 electron beamlets. The resolution of 10 mesh units per millimeter length was used in the simulations. Fig. 3(a) shows the numerically optimized electrodes geometry and helical electron beam. Further Fig. 3(b) shows the zoomed view of electrodes geometry and helical electron beam near cathode region. The zoomed view clearly shows laminar flow of electron beam which is highly desirable to minimize the spreads in beam velocity and energy of HEB. Based on the magnetic field profile given in Fig. 2 and the electrodes geometry shown in Fig. 3, the simulation results confirm the launching of high quality helical electron beam at the cavity center. Fig. 4 shows the growth of beam quality parameters, such as pitch factor and spreads in velocity, with respect to axial distance of MIG. The results in Fig. 4 confirm the electron beam reaches at the cavity center with all desired parameters, i.e., $\alpha \sim 1.5$ and $\Delta\alpha < 5\%$. Table 3 shows final MIG design parameters obtained by EGUN simulations.

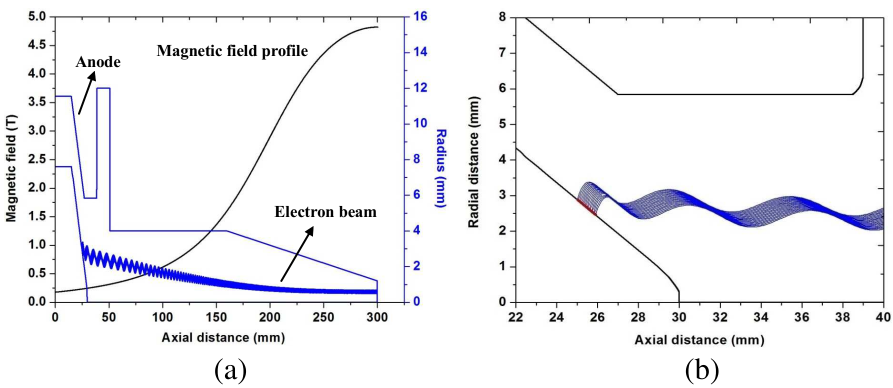
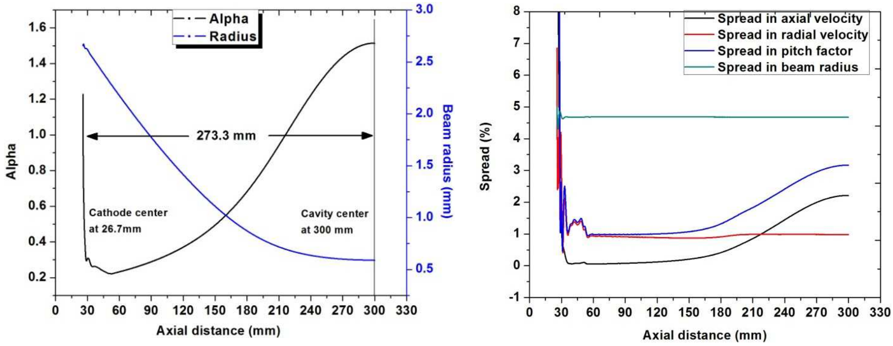


Figure 3. (a) Numerical design of MIG with HEB, electrode geometry and magnetic field profile, (b) zoomed view of MIG design near the emitter (emitter is shown in red color).

4. DESIGN VALIDATION

The designed MIG is further validated in another three dimensional design tool CST-Particle Studio [19, 20]. A 650 kW triode MIG has been designed already for 42 GHz gyrotron by using CST-PS [19] and the similar approach is used in case of 132 GHz gyrotron. Here the magnetic field is much higher (around 3 times) than 42 GHz gyrotron MIG and thus very fine meshing is used in the design of



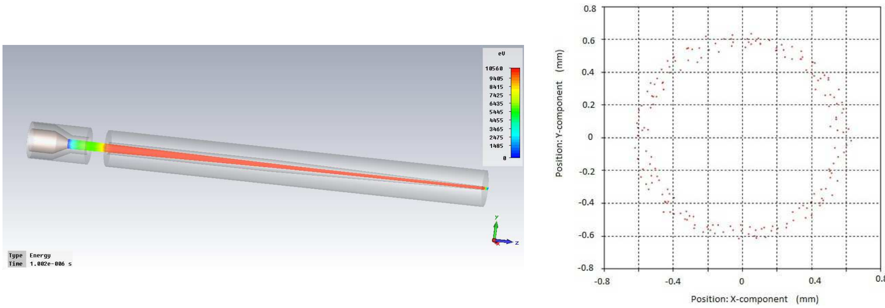
(a) (b)

Figure 4. (a) Pitch factor (α) and beam radius and (b) spread in axial velocity, transverse velocity, pitch factor and beam radius with respect to axial distance from emitter to cavity center.

Table 3. Optimized MIG design parameters.

Cathode magnetic field	0.2328 T
Emitter slant angle	25.8 degree
Compression ratio	20.7
Beam radius	0.59 mm
Pitch factor	1.51
Spread in transverse velocity	1%
Spread in axial velocity	2.21%
Spread in beam radius	4.67%
Spread in pitch factor	3.16%

132 GHz gyrotron MIG. The similar magnetic field profile is applied in CST 3-D simulations as optimized in EGUN simulations. The magnetic field profile is imported directly from the EGUN output files. Fig. 5(a) shows the 3-D geometry of electrodes and electron beam profile. Fig. 5(b) shows the radial position of electron beam at the interaction cavity center. It is clearly shown in figure that all the electrons enter at the cavity center around the beam radius of 0.6 mm. The comparison between the results obtained from EGUN and CST simulations is summarized in Table 4. The results in Table 4 confirm very good agreement between the EGUN and CST-PS designs.



(a) (b)

Figure 5. (a) Three dimensional design of MIG using CST-Particle Studio, and (b) radial position of electron beam at the cavity center.

Table 4. Comparison of CST PS and EGUN results.

Parameters	**CST results**	**EGUN results**
Mean Beam radius	0.58 mm	0.59 mm
Pitch factor	1.48	1.51
Spread in transverse velocity	1.2%	1%
Spread in axial velocity	2.18%	2.21%

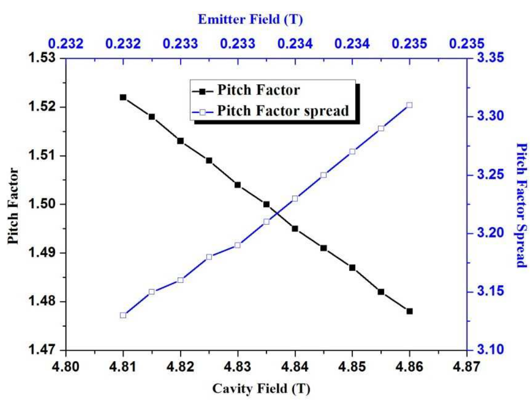
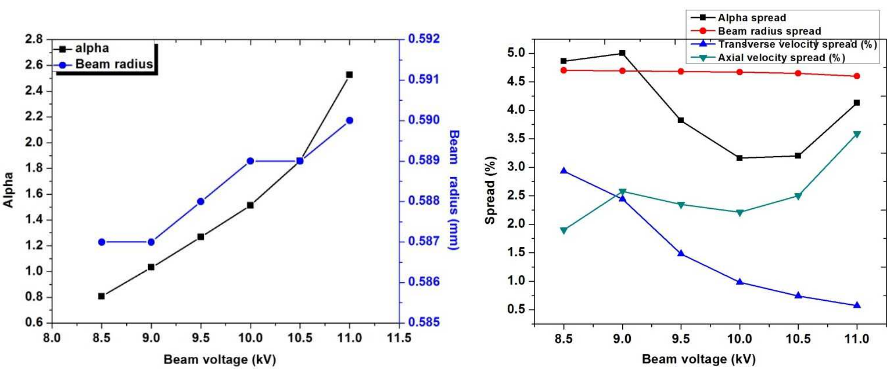


Figure 6. Pitch factor and pitch factor spread (%) with respect to cavity magnetic field and emitter magnetic field (beam voltage = 10 kV, anode voltage = 4 kV, beam current = 50 mA).

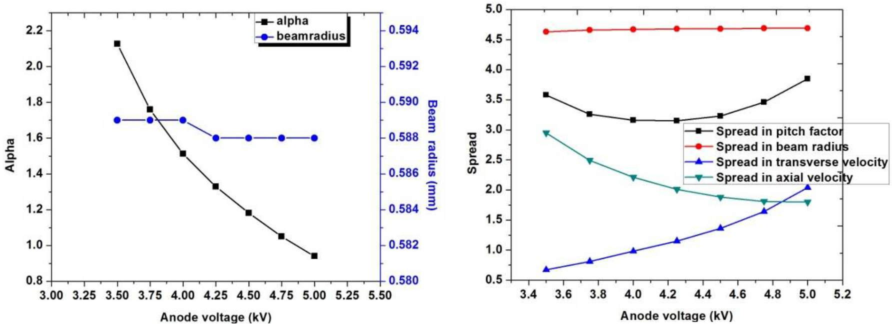
5. PARAMETRIC ANALYSIS

The tunability in DNP gyrotrons can be achieved by varying either the magnetic field or beam voltage. The magnetic field variation provides the frequency tunability in wide band and has been considered for 132 GHz design. Due to the variation in magnetic field at cavity center and emitter, the beam quality parameters (spreads and pitch factor) can be changed or degraded. Considering this point, the parametric analysis is performed for a range of magnetic field at emitter and cavity centers. The range of magnetic field at emitter and cavity centers is decided by the interaction cavity simulations considering the frequency tunability of 2–3 GHz. Fig. 6 shows the variation in pitch factor and pitch factor spread with respect to emitter and cavity magnetic fields. Results in Fig. 6 confirm a high quality electron beam ($\alpha \sim 1.5$, $\Delta\alpha \sim 3.15\%$ to 3.30%) for a range of magnetic field required in frequency tuning. Figs. 7 and 8 show the results of pitch factor and pitch factor spread with respect to beam voltage (also called emitter voltage) and anode voltage. The results confirm small velocity spreads in helical electron beam and high pitch factor in a long range of beam voltage and anode voltage. These parametric analyses would be helpful in the actual fabrication of the device.



(a) (b)

Figure 7. (a) Variation in pitch factor and beam radius with beam voltage, (b) variation in spreads in pitch factor, transverse velocity, axial velocity and beam radius with respect to beam voltage. The fixed MIG parameters are: Cathode magnetic field = 0.2328 T, cavity magnetic field = 4.82 T, anode voltage = 4 kV, beam current = 50 mA.



(a) (b)

Figure 8. (a) Variation in pitch factor and beam radius with anode voltage, (b) variation in spreads in pitch factor, transverse velocity, axial velocity and beam radius with respect to anode voltage. The fixed MIG parameters are: Cathode magnetic field = 0.2328 T, cavity magnetic field = 4.82 T, beam voltage = 10 kV, beam current = 50 mA.

6. CONCLUSION

The design of low spread triode magnetron injection gun is completed for 200 MHz DNP/NMR spectrometer. The design was performed by the beam trajectory code EGUN and further validated by 3D electromagnetic simulator CST-Particle Studio. The design results obtained by EGUN and CST simulations confirm the pitch factor and pith factor spread around 1.5 and 3%, respectively. The design results are validated in a wide range of magnetic field profiles required in frequency tuning. The parametric analyses are also performed to support the estimation of tolerance in the fabrication of actual device.

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