CHAPTER 7

SUMMARY, CONCLUSION AND FUTURE SCOPE

GYROTRON is a high power, millimeter wave oscillator and maintains distinct edge over the other counterparts since its inception around five decades ago. The application spectrum of gyrotron is continuously expanding covering variety of fields. Some of the major scientific applications covering particle accelerators to thermonuclear plasma fusion devices and plasma diagnostics, strategic applications covering radar to missile guidance, industrial applications from millimeter wave controlled heating to material processing and ceramic sintering, medical applications through spectroscopy, etc. Interest in gyrotron research found a quantum jump after its direct use in global activity, such as, International Thermonuclear Experimental Reactor (ITER) program which started to create tokamak (artificial sun), collectively with USA, Russia, European Union, China, Japan, South Korea and India as global partners, to create the facility to produce electricity from fusion power with an aim to solve the problem of future energy generation to a great extent. The activities in the area of gyrotron and gyro-devices span the world covering Russia, China, Japan, European Countries, Australia, USA, etc. Seeing the importance of gyrotron in today and future time, India has also started an activity through a multi-institutional project on gyrotron, namely, “Design and development of 42 GHz, 200 kW gyrotron”. Gyrotron is a new device from Indian research point of view and thus a lot of skill and knowledge are to be required for design and development of this class of device and thus the author is fascinated to select the research topic around the gyrotron development. The research work is distributed into seven Chapters of the thesis, summarized and concluded in brief as follows.

For the generation of high power at the microwave and higher frequencies, electron beam device is the only means. Microwave electron beam devices are of two types, slow-wave and fast-wave devices. In both these microwave tubes, RF power is grown through interaction between the electron beam and the RF waves. But, in a slow-wave microwave tube, the phase velocity of the RF waves are less than the velocity of light whereas in a fast wave microwave tube, the phase velocity of the RF waves are greater than the velocity of light. Gyrotron is basically a fast-wave microwave tube and its schematic showing major assemblies is given as Fig. 1.1. The axial type of gyrotron is shown and also kept within the purview of the present research. In this type of gyrotron, the RF power extraction and the electron beam collection system are kept along the same (axial) axis. The other type of gyrotron is radial type of gyrotron where the RF power extraction and the electron beam collection systems are placed at the mutually perpendicular position.

In the second half of the last century, a new generation of device emerged through theoretical research by Twiss in Australia, Schneider in USA and Gapanov in USSR. The growth of RF was made possible through interaction between fast RF wave and gyrating electron beam and Gyrotron type of devices came into existence. Presently, gyrotron research spans almost the whole world and the most important are USA, Russia, European Union, Australia, China, South Korea, Japan, etc. and now India is also actively participating in this area. A number of commercial gyrotrons of various specifications are now available and Fig. 1.2 shows some of these high power, high frequency gyrotrons. Presently gyrotron development touches MW power and terahertz frequency levels. Table 1.1 presents a brief summary of gyrotron growth since its first development entry which clearly shows that there is quantum jump in the gyrotron performance in terms of output power from 6W to megawatt, operational frequency from 8GHz to tera hertz, operating mode property from the simple rectangular TE_{10} to $TE_{28,8}$ mode, magnetic field strength from 0.3T to 20T, RF window simple mica to CVD diamond and so on to so forth. National scenario is elaborated and this clearly shows that initiation of gyrotron development is a challenge due to limited skill, knowledge and infrastructure. But, slowly and slowly, gyrotron research reached a stage with the development of the inhouse design and development technologies as well as the infrastructure. Further, a number of activities related to gyrotron are presently going at the country under various schemes.

The various applications of the gyrotrons, such as, strategic, scientific, industrial, medical applications are briefly discussed in sub-section 1.1.3. As a researcher, it is essentially important to have clarity about the device operation and thus the two basic constituent assemblies of the gyrotron, that is, electron beam and RF structure are presented in Section 1.2 through emission, transmission and collection of electron beam (sub-section 1.2.1) and then RF generation, propagation and extraction (sub-section 1.2.2). Then, operational principle of gyrotron is discussed through the basic analytical expressions (1.1)-(1.5). The dispersion diagrams for fundamental and harmonic operations are discussed. Finally, the motivation and objective of the present research is outline which is around the design and development of electron gun, RF interaction structure and collector assemblies of the 42GHz, 200kW gyrotron under development at CSIR-CEERI. The detailed plan and scope of this research is also presented chapter-wise in Section 1.4.

Gyrotron gun-collector module is basically an assembly of gyrotron MIG gun and collector. Thus, gyrotron electron gun and collector design are discussed in this thesis. As the design of the gyrotron electron gun directly depends upon the operating mode and the magnetic field at the gyrotron RF interaction cavity and these parameters are optimized in the course of interaction cavity design. Thus, the interaction cavity used between gun and collector is very important component and thus has also been included in the present study, design and development. The development and characterization of gyrotron gun-collector module has been also successfully carried out and presented in the thesis. All the above-mentioned aspects are elaborated in Chapters 2-6 as follow.

Chapter 2 presents the design of gyrotron electron gun, known as the magnetron injection gun (MIG) to be incorporated in the 42GHz, 200kW gyrotron. Obviously, MIG is introduced with its basic functional aspects. There are two types of MIG normally used in the gyrotron, namely, diode-type and triode type have been discussed and shown in Fig. 2.1. In diode-type MIG only two electrodes, namely, cathode and anode (also called as control anode) are used, where a high voltage is applied in between them. In triode-type MIG, three electrodes are used with the employment of one intermediate anode in between cathode and control anode. The intermediate anode known as the modulating anode is kept at higher potential with respect to the cathode potential but lower than the control anode potential. For the 42GHz, 200KW gyrotron, the triode type of MIG has been selected where employment as the additional electrode provides better control on the electron beam transmission. Various types of electron emitters, that is, cathodes used in the MIG has also been discussed. The dispenser cathode has been selected for the present case due to its lesser poisoning effect. For the design of MIG, at first, synthesis approach of Baird and Lawson is used and presented with simplicity in Section 2.1. All the important analytical expressions, (2.5)-(2.24), have been given to find the various MIG parameters related to the cathode, anode and electron beam. These synthesized design parameters are cathode radius, cathode width, cathode slant angle, anode radius, cathode-anode distance, etc. for MIG electrodes, namely, cathode and anode while magnetic compression ratio, magnetic field at cathode, beam voltage, beam current, transverse-to-axial beam velocity ratio, cathode current density, ratio between the cathode current density, the space-charge-limited current density, etc for electron beam. The technical limiting values of the MIG parameters are spelt in Table 2.1. Based upon the analytical expressions (2.5)-(2.24) is computer code has been developed and used to estimate the synthesized design parameters for this 42GHz gyrotron gun. Further, the gyrating electron beam trajectory analysis has been carried out using the available software EGUN (Section 2.2) to analyze and optimize the MIG geometry as well as electron beam parameters (Table 2.2). It is worth to mention that the operating mode TE_{03} and magnetic field at interaction cavity =1.61T have been used for the MIG design and these parameters are optimized during the design of the RF interaction cavity (Chapter 4). Fig. 2.3 shows the optimized electron beam trajectory and MIG geometry obtained through EGUN code. It has been found that the final optimized values of the MIG parameters: cathode radius = 22.55mm, cathode slant width = 7.0mm, cathode angle = 28°, transverse-to-axial beam velocity ratio = 1.26, magnetic compression ratio =14.9, beam voltage = 65 kV, beam current = 10A, modulating anode voltage = 29kV, etc. In actual practice, a misalignment usually get develops while placing the gyrating electron beam in a gyrotron cavity concentrically with the system axis of cavity and the system axis of magnetic field and this misalignment of electron beam axis from the system axis affects the gyrotron operation. Thus, misalignment of electron beam is also studied with respect to the cathode position and magnetic field in the practical scenario.

The developed 42GHz MIG has also been explored for its applicability for the other frequencies devices as well, in Section 2.5. In this process, it has been found that the 42GHz, 200kW MIG can also be used for a 28GHz gyrotron of 100kW output power. For this purpose, the RF interaction structure to be used for 28GHz gyrotron has to be accordingly designed. The basic specification of the 28GHz gyrotron has been given in Table 2.4 which states the operating mode as $TE_{3,2}$ and the beam launching position is 5.1mm in the cavity. The optimized MIG parameters have been presented in Table 2.5 while the electron beam trajectory shown in Fig. 2.12. This study helps to develop a 28GHz gyrotron by using the same developed MIG. In this manner, more number of gyrotron can be developed by using the same most complex sub-assembly of gyrotron, that is, the gyrotron electron gun, MIG.

The cathode heater subassembly is an essential component of MIG and was developed by the integration of cathode with filament heater as a single subassembly. When cathode surface achieve certain temperature then it starts emitting electrons and this cathode surface temperature enhancement is usually made with the use of heater filament. Normally, tungsten cathode operates above 1000°C and for this the filament heater is kept at a higher temperature. Thus, the cathode-heater assembly has been thermally designed taking aid of ANSYS code and toroidal shaped filament hearer made of tungsten wire is finally optimized and used for this purpose (Section 3.2). Fig. 3.1 shows the schematic of cathode-heater assembly for the 42GHz gyrotron and Table 3.1 presents the list of the materials used in the cathode heater. The annular shaped M-type dispenser type of cathode is selected for use in the 42GHz gyrotron for better life and reliability. The optimized dimensions of filament heater are heater wire diameter, heater helix diameter, heater helix pitch, toroidal heater position diameter are 0.75mm, 4.00mm, 1.50mm and 33.00mm, respectively. The toroidal heater position diameter is the diameter of a circle around which the filament heater is supposed to be positioned so that the filament heater is in contact with the cathode base. The designed cathode-hearer assembly has also been fabricated by M/S Semicon, US for sake of confidence and time constraint. The designed cathode pellet has also been procured (Fig. 3.7) and dimensionally measured and found to be satisfactory (Table 3.3).

The cathode-hearer assembly procured from M/S Semicon has been thoroughly characterized. The characterization has been carried both independently in a bell-jar system and in the complete gyrotron electron gun in two different situations, namely, during vacuum processing and testing. A bell-jar system has been developed (Figs. 3.8- 3.9). Fig. 3.8 shows the typical hot condition of cathode and Fig. 3.9 the temperature measurement of the cathode. The disappearance filament type pyrometer is used to measure the temperature of cathode all around 360°. Argon gas is used as the environment around the cathode-heater assembly due to limited condition. V-I characteristics of heater along with cathode surface temperature in the Argon gas atmosphere of $4.35\text{x}10^{-04}$torr has been shown in Fig. 3.10. After mounting the assembly in vacuum bell-jar, at first, low heater voltage equal to 2.5V is applied and cathode surface temperature is observed with the help of the disappearance filament type pyrometer. Then, the heater voltage is increased slowly upto 9V (Fig. 3.9). The sufficient time is provided at each step to reach temperature stability. The cathode temperature 1080°C was achieved with the heater power < 350W.

The magnetron injection gun (MIG) type electron gun is usually used in the gyrotron. The characterizations of cathode-heater assembly, particularly cathode have also been carried out during vacuum processing and testing of MIG (Figs. 3.11- 3.14). Figs. 3.12 and 3.14 present the

V-I characteristics of heater during MIG vacuum processing and testing, respectively. The comparisons of heater characteristics in different systems have been made in close agreements (Table 3.4)

The operating mode and magnetic field of the gyrotron RF interaction cavity are the basic input for the design of MIG and the RF cavity parameters are optmized through cavity design and thus the study of gyrotron RF interaction cavity of the 42GHz, 200kW gyrotron was carried out and presented in Chapter 4. At first, the different types of RF structures used as the RF interaction cavities for the gyrotrons for low frequency, low power to high frequency, high power regimes were discussed, such as, simple cylindrical cavity, co-axial cavity, complex cavity, confocal cavity, photonic band gap cavity, etc. In the first gyrotron, that is, the 42GHz, 200KW gyrotron, the most common cavity, namely, three section cylindrical cavity has been selected. Three sections of the gyrotron cavity are the uniform middle section serving as the RF power growth region, the down taper section at one end serving as the cut-off region for the RF propagation towards the electron gun end while the third section, the up-taper section at the another end of the RF growth region serving as the RF propagating region towards the RF extraction system. The down-taper section, normally called as the input section and the up-taper section, called as the output section. Obviously, for design of the gyrotron RF interaction cavity, at first synthesis has been carried-out (Section 4.2). Synthesized RF cavity parameters, such as, cavity radius, quality factor, state oscillation current, coupling coefficient, wall loss, voltage depression and limiting current was analytical expressed through (4.1)-(4.13). Then, operating mode selection mechanism has been discussed in sub-section 4.2.3. All the basic mode selection parameters were estimated for various possible operating modes and has been presented in Table 4.1. The various operating modes were subjected to the limiting values of voltage depression (<10% beam voltage), limiting current (2 times the beam current) and wall loss (< 0.5kW/cm$^{2)}$ (Chapter 2) . TE$_{03}$ mode with the second maxima as the electron beam launching radius (= 6.06 mm) was found as the most suitable operating mode for the 42GHz, 200kW gyrotron as voltage depression = 1.44kV, limiting current = 59A and wall loss = 0.049kW/cm^2 for this mode. Then, TE$_{03}$ mode was also studied for other mode selection parameters, that is, start oscillation current and coupling coefficient and found as the suitable from mode competition point of view.

A generalized nonlinear theory for a gyrotron in the form of normalized parameters has been described and all the relevant parameters of electric field, cavity length, magnetic field, etc.

were presented through (4.14)- (4.17) in Section 4.3. Then, the transverse efficiency plots were constructed as a function of generalized electric field and electric length for various normalized magnetic field detuning parameters as shown in Figs. (4.1)-(4.4) which were used to obtain these parameters for the maximum transverse interaction efficiency (Table 4.2). Out of these ranges, the best transverse interaction efficiency ~ 65% was achieved using the values given in Table 4.1 and then using (4.3) and the beam parameters related to beam voltage = 65kV and beam current = 10A. The values of these normalized parameters for the best efficiency were obtained as F=0.14, μ=10.17 and Δ=0.51 for the 42GHz, 200KW gyrotron. Then, the plots between the normalized energy and the normalized length have been obtained for a number of electrons throughout the length of cavity and shown in Figs. 4.5 and 4.6 which were used to obtain the transverse interaction efficiency through (4.4). The magnetic field, the cavity RF power growth length and the electron velocity ratio have been calculated by using these generalized parameters and were obtained as 1.615T, 44mm and 1.4, respectively for the 42GHz, 200kW gyrotron. These parameters were initially used for beam wave interaction simulation for the final optimization of the gyrotron cavity (Section 4.4).

The beam-wave interaction simulation has been carried out through commercial PIC code MAGIC in Section 4.4. Oscillation frequency and power growth results obtained from MAGIC at 42GHz frequency ~ 275kW output power has been generated and the typical results have been presented in Figs. 4.8 and 4.10, respectively. In this beam-wave interaction PIC simulation, the complete geometry of the interaction structure was optimized including both the input and output taper sections. The optimized geometry of the interaction structure for the 42GHz, 200kW gyrotron has been given in Table 4.3. The sensitivity analyses of the various parameters have also been carried out to observe the fabrication tolerances. Comparison between the results obtained from the generalized nonlinear theory and MAGIC PIC code has also been found in satisfactory agreement (Figs. 4.11 and 4.13).

The fabricated actual gyrotron interaction cavity has been characterized for RF parameters, in the cold condition, related to the eigenfrequency, the quality factor and the electric field profile through both (i) destructive and (ii) non-destructive methods. Various characterization methods have been studied and presented in Section 4.5. A hole was made in the RF interaction cavity for the measurement through destructive method (Fig. 4.14) while no change was required in the cavity structure for the non-destructive method (Figs. 4.15 and 4.16).

The theoretical and measured values of the resonant frequency and quality factor of the RF cavity satisfactorily agreed, as shown in Table 4.4.

As mentioned earlier, the 42GHz MIG can also be employed in a 28GHz gyrotron. However, the interaction structure has been redesigned for the geometrical dimension and the operating mode. The design of a 28GHz gyrotron interaction cavity with the use of the 42GHz MIG has also been described in Section 4.6. $TE_{3,2}$ operating mode has been found to be the best for the 28GHz gyrotron with the magnetic field 1.0T for beam voltage = 65kV and beam current = 10A. Nonlinear analytical results was also found for the 28GHz gyrotron and presented as Figs. 4.17 and 4.18. Fig. 4.17 confirmed energy transfer from the electron beams to the RF field while Fig. 4.18 show the phase bunching of the gyrating electron beam for the 28GHz gyrotron cavity. Figs. 4.19 and 4.20 exhibited the simulation results obtained using PIC code MAGIC. The temporal growth of the RF power were shown in Fig. 4.19 and confirms the RF power growth >100kW.

Collector assembly of the gyrotron is used to collect the spent electron beam which is the beam of reduced energy obtained after the beam-wave interaction process. The spent electron beam is having reduced energy compared with that contained by the electron beam generated from the MIG. In the 42GHz, 200kW gyrotron, the energy of the spent beam was ~450kW, since the 200kW RF was grown due to transfer from the 650kW energy of the generated electron beam. The collector design thus important due to its handling of the high energetic electron beam. Chapter 5 presented the collector design of the 42GHz, 200kW gyrotron. There are two types of collector, namely, undepressed and depressed, were described mentioning their difference and advantages. In undepressed scheme, the collector is kept at the same potential as of the control anode, while at different potential in depressed collector. The efficiency enhancement is main advantage of the depressed collector systemapart from thermal management and high voltage DC power supply. However, the gyrotron with undepressed collector was used in the present work due to lesser (i) technological complexity in its fabrication resulting from the use of different electrodes and ceramics in between, (ii) complex power supply for operation of applying different potentials on various electrodes of collector, (iii) as well as overall cost factor.

For the sake of simplicity and easiness, the schematic view of gyrotron collector system and collector design approach system have been presented in Figs. 5.1 and 5.2, respectively.

Then, a design flow for collector has been developed (Fig. 5.3). The initial design of collector was obtained for the estimation of collector dimension for the specific power dissipation though (5.1)-(5.2) and reported as Table 5.1. Afterwards, the electron beam spread analysis has been carried out with the help of EGUN code (Section 5.3). The analyses have been carried for various values of collector dimensions with and without magnetic field around the collector. The optimized uniform electron beam spread = 330mm in a collector of length = 800mm and diameter = 85mm have been obtained. The optimized electron beam spread has been achieved with the equal values of magnetic field values of both magnetic systems located at the same axial positions but the different radial positions. The three magnetic field systems have also been optimized to be axially located at 935mm, 1045mm and 1175mm, respectively, which present distances from the collector opening end as 185mm, 295mm and 325mm, respectively, as the collector end was at 750mm from the beam spread one end location. The optimized positions and values of the magnets summarized in Table 5.2.

The thermal analysis is also important for the collector design, due to its handling of large electron beam energy. The thermal analysis of collector has been carried-out using ANSYS code to estimate the thermal behavior to ensure that collector does not softened or melted due to incident of high energetic electron beam. The flow diagram for the thermal analysis has been shown in Fig. 5.7. The properties of OHFC copper used as the collector material and water used as the coolant have been given in Tables 5.3 and 5.4. Various heat film coefficients have been tried to find its reasonable value so that the collector inner wall temperature becomes less than 200^{o}C and coolant water temperature is less than 40^{o}C (Figs. 5.11-5.12). The thermal analyses of collector with and without axial grooves have been carried-out with the observation of obvious advantage of the axial grooves (Fig. 5.12). The optimized values for the axial grooves have been found as: number of axial grooves on the outer surface = 18, groove thickness = 4mm, groove height = 16mm, groove width = 4mm and space between two grooves = 16.5º.

The thermal analyses have also been carried for various inlet water temperatures in the range of 288°K -293°K and hydraulic diameters ranging from 4- 4.5- 5mm diameter. Two cases of power dissipations have been studied, such as, (i) 450kW dissipated spent electron beam power when 200kW RF power is generated and (ii) total 650kW spent electron beam power when no RF power is generated. It has been found that in both cases, the temperatures of both inner and outer surfaces continuously decrease with increase in water flow rate in all the situations. It is always desired to achieve the inner OFHC collector surface temperature around or less than 473°K which has been obtained through these simulated results. The typical thermal analysis results, for both situations related to 450kW and 650kW power dissipations, have been shown in Figs. 5.13 and 5.14. Further, the transient thermal studies have been carried-out to estimate the maximum rise of temperature before the steady state for 450kW and 650kW power dissipations for different water flow rates showing the temperatures of inner and outer surfaces of the collector. From these simulated results presented in Figs. 5.15 and 5.16, it was found that in all the cases the inner and outer temperature rise times become constant after 2-3 sec and decreases with increase in water flow rate.

The actual collector designed for the 42GHz, 200kW gyrotron is not a viable idea to use in the gun-collector module due its large size. Thus, a test collector of reduced dimension of length = 150mm and outer diameter = 100mm has been designed. The test collector has been subjected to both steady state and transient thermal analyses as per requirement of the characterization of gyrotron MIG. Figs. 5.17- 5.20 presented the typical results of the inner and the outer wall temperatures with 100W, 1000W and 2500W dissipated heat powers, respectively. The transient thermal analysis has also been carried out to see the steady state temperature rise to find that after ~10 minutes, the steady state condition is reached with temperature rise upto ~120^{o}C with heat film coefficient equal to 100W/(m^{2}K) for dissipated heat power.

The development and characterization of gyrotron gun- collector module for the 42GHz, 200kW gyrotron has been presented in Chapter 6. The cathode-heater assembly procured from M/S Semicon has been used in the development of the gyrotron gun-collector module and discussed in Section 6.2. Fig. 6.1 shows the schematic of MIG of the 42GHz, 200kW Gyrotron with the complete piece-parts. List of all piece-parts consisting of name, quantity and number has been presented in Table 6.1. It is worth to mention that a joining sequence of piece-parts for development of the complete MIG has been developed and used to develop the gun collector module having MIG as its main assembly. Most of the developmental steps were carried-out at CEERI and help of BEL, Bangalore was also taken for the final assembly. It is worth to mention that the test collector designed in Section 5.5 has been fabricated and employed in the development gyrotron-electron gun module (Fig. 6.3). The developed gun-collector has been properly vacuum processed at BEL upto 400°C and the holding time was ~ 40 hours. Finally, the vacuum processed gun-collector module has been brought to CEERI for further testing. MIG has been thoroughly characterized for various tests, such as, continuity, vacuum, voltage breakdown, electron beam emission, etc. The protocol for testing of MIG was also prepared (Table 6.2). All these tests have been carried-out and found within the desirable values as mentioned in Table 6.2 (Section 6.3). The electron beam emission test has been carried out with limited high voltage due to non-availability of the infrastructure (Sub-section 6.3.4). However, the comparative study of experimental (shown by solid line) and analytical (shown by dotted line) given in Fig. 6.12 clearly shows a satisfacory agreement. The electron beam transmission test has also been carried-out and it was found through this test that as per design, the electron beam gets transporated to the control anode instead of the modulating anode. Successful design, development and characterization of MIG is noteworthy and gives lot of confidence in the field of gyrotron research and development.

7.1 Limitation and Scope for future Work

The thesis presents the design, development and characterization of the gyrotron electron gun, that is, the MIG, RF interaction cavity and collector for the 42 GHz, 200 kW gyrotron presently under development for the first time in India. All these steps for design, development and characterizations have been carried out through development of in-house technology and infrastructure. The thermal analyses of some components have been discussed but the complete thermal analysis is required to be done in long pulse operation of gyrotron. The tests of MIG, particularly, the electron beam tests have done upto the limited voltage and thus the electron beam tests upto the rated high voltage is required to be carried out after the establishment of the proper experimental infrastructure such as power supply, cooling arrangement, etc.

The developed MIG has been used for the 42GHz gyrotron and thus, behavior of the MIG needs to be seen and obviously becomes the scope for the further research. The successful development of the 42GHz MIG opens further research and development of high power MIG for various types of gyrotrons, such as, 95GHz, 100kW gyrotron, 170GHz, 1MW gyrotron as well as 1Terahertz, 1kW gyrotron.