ABSTRACT

GYROTRON is a high power, millimeter wave oscillator and maintains distinct edge over its other counterparts since 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 was 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. 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.

Gyrotron is basically a fast-wave microwave device, a new generation of device emerged in the second half of the last century, through basic research by Twiss in Australia, Schneider in USA and Gapanov in USSR. A number of commercial gyrotrons of various specifications are available presently and its development touches MW power and terahertz frequency levels. The gyrotron growth since its first development 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 complex $TE_{28,8}$ 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 that the initiation of gyrotron development is started with a challenge due to limited skill, knowledge and infrastructure. But, slowly gyrotron

research is reaching a stage with the development of the in-house 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 are related to the strategic, scientific, industrial, medical applications. 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 through emission, transmission and collection of electron beam and then RF generation, propagation and extraction. Then, operational principle of gyrotron is discussed through the basic analytical expressions. The dispersion diagrams for fundamental and harmonic operations are discussed. Finally, the motivation and objective of the present research is outlined, 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.

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. 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 all the important analytical expressions 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 and the space-charge-limited current density, etc for electron beam. A 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 to analyze and optimize the MIG geometry as well as electron beam parameters. 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).

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 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 redesigned. 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. Normally, tungsten cathode operates above 1000^{o}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. The annular shaped M-type dispenser type of cathode is selected for use in the 42GHz gyrotron for better life and reliability. The toroidal heater position diameter is the diameter of a circle around which the filament heater is supposed to 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 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 and used for the temperature measurement of the cathode. The disappearance filament type pyrometer is used to measure the temperature of cathode all around 360^o. Argon gas is used as the environment around the cathode-heater assembly. 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. The V-I characteristics of heater during MIG testing has been observed and the comparisons of heater characteristics in different systems have also been found in close agreements.

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 optimized 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. In the 42GHz, 200KW gyrotron, the most accepted open-ended RF 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. 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. Then, operating mode selection mechanism has been discussed and all the basic mode selection parameters were estimated for various possible operating modes. 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 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. Then, the plots between the normalized energy and the normalized length have been obtained for a number of electrons throughout the length of cavity which were used to obtain the transverse interaction efficiency. The magnetic field, the cavity RF power growth length and the electron velocity ratio have been calculated by using these generalized parameters. These parameters were initially used for beam wave interaction simulation for the final optimization of the gyrotron cavity. The beam-wave interaction simulation has been carried out through commercial PIC code MAGIC. Oscillation frequency and power growth results obtained from MAGIC at 42GHz frequency ~ 275kW output power has been generated. 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. 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.

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. A hole was made in the RF interaction cavity for the measurement through destructive method while no change was required in the cavity structure for the non-destructive method. The theoretical and measured values of the resonant frequency and quality factor of the RF cavity satisfactorily agreed.

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. $TE_{3,2}$ operating mode has been found to be the best for the 28GHz gyrotron for the RF power growth >100kW with the magnetic field 1.0T for beam voltage = 65kV and beam current = 10A.

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. 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.

The initial design of collector was obtained for the estimation of collector dimension for the specific power dissipation. Afterwards, the electron beam spread analysis has been carried out with the help of EGUN code. The analyses have been carried for various values of collector dimensions with and without magnetic field around the collector. 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 for different axial location and the optimized positions and values of the magnets have obtained.

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. 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 $40^{o}C$. The thermal analyses of collector with and without axial grooves have been carried-out with the observation of obvious advantage of the axial grooves. The typical thermal analysis results, for both situations related to 450kW and 650kW power dissipations. Further, the transient thermal studies have been carried-out to estimate the maximum rise of temperature before the steady state for different water flow rates showing the temperatures of inner and outer surfaces of the collector.

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 has been designed and subjected to both steady state and transient thermal analyses as per requirement of the characterization of gyrotron MIG. 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. 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. It is worth to mention that the test collector designed has been fabricated and employed in the development gyrotron-electron gun module. The developed gun-collector has been properly vacuum processed. 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. The electron beam emission test has been carried out with limited high voltage due to non-availability of the infrastructure. However, the comparative study of experimental and analytical 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.

In the last chapter, Chapter 7, the work embodied in the thesis are summarized. The conclusions of the work are described and findings are discussed. Additionally, the limitations of the present study are discussed. The future scope and extension of the present work is also outlined at the end.