Chapter 7: Summary, Conclusion and Future Scope

7.1. Summary and Conclusion

In the present thesis, rigorous theoretical investigations were carried out to explore tunable gyrotron oscillators' capabilities for DNP / NMR spectroscopy applications. The design, electromagnetic analysis, particle-in-cell (PIC) simulation, and most importantly the tunable bandwidth enhancement were the major focus of the present thesis. The Multimode studies of millimeter-wave gyrotrons were used to investigate the beam – wave interaction phenomenon, not only for the operating modes but also for competing modes, indicating that competitive modes were well suppressed. In addition, the design of various RF interaction structures for millimeter-wave gyrotron was studied to increase the tunable bandwidth of gyrotrons. The magnetic tuning has been performed by varying the magnetic field to obtain tunable bandwidth. The tunable bandwidth has further been increased using another technique namely thermal tuning that is independent of the magnetic tuning. Therefore, the total tunable bandwidth has been obtained by combining the individual tunable bandwidth obtained from the magnetic and the thermal tuning schemes. The major sub-assemblies including the RF window and collector have been studied. A photonic band gap cavity has been used as an RF interaction cavity to increase the tunable bandwidth using the magnetic tuning scheme alone. The tunable bandwidth has further been enhanced using a multi-section slightly tapered cavity. In addition to the above, a sub-millimeter-wave second harmonic gyrotron has been investigated to improve its tuneability for NMR spectroscopy applications.

A review of the present literature has been estimated on the historical development of microwave tubes. Microwave tubes have been discussed about their output power with the corresponding frequency showing that the gyrotron oscillator can produce a few tens of Watts of power in the millimeter, submillimeter and THz wave regimes. The microwave tubes have been well-reviewed in that it has been found that the gyrotron can produce CW power for more than ~ 50,000 hours, which is a basic requirement for DNP / NMR spectroscopy applications. The design point has been estimated as the cyclotron angular frequency with the help of CRM interactions of the gyrotron oscillator. Finally, after a rigorous literature review of DNP / NMR gyrotrons, the problems/limitations of millimeter-wave gyrotrons have been explored, which have been attempted as much as possible to solve them.

In Chapter 2, both linear and nonlinear theories were revisited to investigate the beam-wave interaction mechanism of gyrotron. The linear theory has been used to describe the start oscillation conditions that provide the position of the beam current of the operating mode and other nearby modes concerning the DC magnetic field. The design parameters of the cavity have been optimized by observing the optimum cavity field profile. The non-linear time-dependent Multimode analysis has been used to investigate the fully nonlinear behavior of beam-wave interaction mechanisms in gyrotrons. As a result, the output power, efficiency, and bunching phenomena of the gyrotrons were estimated. These analyses were generalized to include the instrument operations by employing any arbitrary shapes of RF interaction structures in any arbitrary cyclotron harmonics. An independent computer code has been developed for the Multimode analysis to investigate beam-wave interactions and calculate the RF output power and efficiency. A 260 GHz tunable gyrotron operating in $TE_{7,2}$ mode using a conventional tapered cylindrical cavity has been chosen for the design analysis and benchmarking of the code with a detailed design specifications existing in the literature. The design methodology has been discussed in detail with limiting constraints. The coupling coefficient has been calculated to obtain the optimal beam radius at which the maximum coupling occurs between the RF wave electron beam. The calculation of the start oscillation current has helped to select an appropriate axial magnetic field at which the maximum beam-wave interactions occur to achieve the optimal saturated output power. An output power of ∼163 W was observed in the operating $TE_{7,2}$ mode and negligible power in the competing modes. The present analytical results from the Multimode code have been benchmarked against an experimental work reported by Alberti *et al.* and found that they are in good agreement.

In Chapter 3, the PIC simulation has been carried out to observe the beam-wave interaction behavior of 260 GHz gyrotron. The results obtained from the PIC simulation has also been validated by using the Multimode theory discussed in Chapter 2. In PIC simulations, ∼150 W power was observed in $TE_{7,2,1}$ mode, and negligible power is obtained in other competing modes like $TE_{4,3}$, $TE_{2,4}$, etc. The resonating frequency was calculated as 260.46 GHz. The calculation of the start oscillation current (SOC) for the axial mode numbers, $q = 1 – 6$, were done, which provides an idea to excite a series of axial modes in the RF cavity in a span of the magnetic field. The thermal analysis has been performed using the ANSYS simulation tool to observe the effect of ohmic loss on the RF interaction cavity. To achieve the gyrotron's tunable bandwidth, the magnetic tuning has been performed by varying the magnetic fields, which provide ~ 1.3 GHz (260.46 GHz – 261.76 GHz) tuneable bandwidth. In addition, the tubule bandwidth has been enhanced using the thermal tuning scheme as ~ 0.58 GHz. Therefore, the total tunable bandwidth has been obtained as ~ 1.88 GHz. In addition, a single disk window was designed to extract the output power from the cavity. Finally, a single-stage depressor collector has been designed which was analyzed by using ANSYS for thermal and structural analyses.

In Chapter 4, to alleviate the mode competition problem in the RF cavity, the PBG structures have been introduced, which provides mode selective operation. A 2D triangular lattice of PBG structures has been chosen to design the PBG cavity due to its azimuthal symmetry. The metal rods have been used from the regular PBG structures and the PBG cavity has been realized by removing certain number of rods from the centre of the structures. The dispersion relations and the global band diagrams have been calculated using the Alternate Direction Implicit – Finite Difference Time Domain (ADI-FDTD) method. The mode analysis has been performed to observe all the possible modes that fall in the global bandgap's stopband. The time-domain and Eigenmode analyses have been performed to observe the PBG cavity's transient and electromagnetic behaviors. To observe the beam-wave interaction process, PIC simulation has been performed. The PIC simulation of the present PBG gyrotron predicted a CW peak power ~121 W in $TE_{7,2,1}$ –like mode and negligible power in other competing modes like $TE_{4,3}$ and $TE_{2,4}$. For the confined mode, the PIC simulation results have been validated with the Multimode theory by assuming that the PBG cavity behaves like a conventional cavity. To achieve the tunable bandwidth, the magnetic tuning has been performed that predicted ~ 1.5 GHz (260.32 GHz – 261.85 GHz) tuneable bandwidth, which is higher than ~1.3 GHz tunable bandwidth obtained from the conventional gyrotron by the magnetic tuning only. Due to the large transverse dimension of the PBG cavity, the effect of ohmic loss in the PBG gyrotron becomes very low as compared to the conventional gyrotron. The thermal analysis of the PBG cavity has been performed in CST Mphysics. To observe the rods' deformation, the structural analysis has been performed in ANSYS by using the obtained temperature in CST Mphysics. The Eigenmode Solver has been used to observe the effect of the PBG rods' deformation on the resonating frequency of the cavity, which shows only ~7 MHz shifting in resonating frequency. Therefore, the PBG cavity would be useful to have a stable operation in gyrotrons.

In Chapter 5, the multi-section slightly tapered cavity has been designed by modifying the RF cavity discussed in Chapter 3. The multi-section cavity's design parameters have been optimized by observing the effect of modifications on the resonating frequency and diffractive Q factor. The multi-section cavity field profile has been calculated for axial mode number, q = 1 – 9. Further, the effective length and quality factors (Q_d and Q_{ohm}) have been calculated. The start oscillation current has been calculated for q = 1 – 9, which provides the magnetic field span in which a series of axial mode numbers can be excited. The PIC simulation of a multi-section cavity-based gyrotron generated a continuous peak power ~ 114W in the $TE_{7,2,1}$ mode and negligible power in other competing modes such as $TE_{4,3}$ and $TE_{2,4}$. The resonating frequency has been observed as ~260.05 GHz. The magnetic tuning has been performed by varying the magnetic fields from 9.51 T – 9.74 T which provide the tunable bandwidth as 1.85 GHz (260.05 GHz – 261.90 GHz) that is ~0.55 GHz higher than the obtained tuneable bandwidth in a conventional gyrotron of Chapter 3. Further, the tunable bandwidth has been enhanced by using thermal tuning as 0.47 GHz. Therefore, the total tunable bandwidth has been obtained as ~2.32 GHz which will be beneficial for DNP / NMR applications.

In Chapter 6, a submillimeter-wave second harmonic gyrotron has been modeled to operate in $TE_{11,2}$ mode at 527 GHz for DNP / NMR applications. The Multimode simulations predicted ~11.5 W power in $TE_{11,2}$ mode at ~527.20 GHz, which predicts a good agreement with an experimentally tested gyrotron by Jawla *et al.* at MIT, USA. The tunable bandwidth has been obtained as ~0.31 GHz while magnetically tuning the gyrotron. Further, the tunable bandwidth has been increased to ~0.30 GHz by using the thermal tuning. Therefore, the total tunable bandwidth has been obtained as ~ 0.61 GHz.

7.2. Limitations of the Present Work and Scope for Further Studies

The present thesis focused on enhancing the tunable bandwidth of the millimeter-wave and submillimeter-wave gyrotron operating at ~260 GHz and ~527 GHz for 400 MHz and 800 MHz NMR spectrometer, respectively. The tunable gyrotron can be extended operating in higher-order mode in the THz regime for more than 1 GHz NMR spectroscopy applications. In the present study, the magnetic and thermal tuning schemes have been used to achieve the tunable bandwidths of gyrotrons. The tunable bandwidth of the gyrotron can further be enhanced by using the strong external reflections from the output waveguide section of the gyrotron.

In the present thesis, the theory and PIC simulations described in detail were based on the assumption of axial symmetry of the electron beam in the cavity. In practice, the annular electron beam cannot be placed symmetrically in the gyrotron cavity as it affects the operation of beam-wave interaction in the gyrotron cavity. The present study can be extended to the effect of beam-misalignment on the tunable bandwidth of the gyrotron.