Chapter 7: Conclusion, Summary and Future Scope

7.1 Summary and Conclusion

In the present thesis, rigorous theoretical studies of X-band gyro-twystron were made to explore the new possibilities and capabilities of gyro-twystron. The design, electromagnetic analysis, and 3D simulation were a major focus of the thesis. A benchmarking study is carried out by extending the single-mode analysis to multimode analysis, which predicted that TE_{02} mode is most troublesome. A design study of gyro-twystron was made to suppress the TE_{02} mode using the periodic dielectric loading in the output waveguide section. Further, the stability analysis of PDL gyro-twystron was made and PDL gyro-twystron was designed. The multimode study of PDL gyro-twystron was made to investigate the behaviour of multiple modes, which predicted that TE_{02} mode was well suppressed. Two major subassemblies such as coupler and RF window, were studied. An intermediate cavity was introduced to single cavity gyro-twystron to improve the performance metrics of two cavity gyro-twystron. The theoretical developments and findings of the present thesis were discussed below.

This literature review projected the evolution and historical developments of microwave tubes. The development of conventional VEDs was discussed in chronicle order with the taxonomical description and operating principle. The stagnation in developments of conventional microwave tubes and discovery of CRM mechanism ignites the development of gyrotron devices, which were dominantly discussed in the Literature review. Gyrotron amplifiers were reviewed thoroughly, and the research advancement of gyro-klystron and gyro-TWT were discussed along with slow-wave twystron amplifier. Finally, the oscillations and parasitic instabilities in high power operation of the gyro-twystron amplifier were identified as problem/limitations. the literature review was intensively investigated for viable solutions to suppress oscillation and parasitic instabilities.

In Chapter 2, beyond the verbatim boundary of gyro-twystron review, mathematical aspects of gyro-twystron theory were scrutinised to study the beam-wave interaction behaviour. The design methodology of gyro-twystron was developed, and for beam wave interaction study, an available single-mode nonlinear of gyro-twystron was extended as multimode theory. These theoretical developments were benchmarked with an experimental X-band gyro-twystron, and the multimode analysis predicted 20 MW of RF power in TE_{01} and 1 MW of RF power in second harmonic TE_{02} mode.

In Chapter 3, PIC simulation of X-band gyro-twystron was carried out to validate the analytical studies discussed in Chapter 2. The 3D simulation results of beam-wave interaction were discussed, which helps to understand and visualise the physics of gyro-twystron. The PIC simulation predicted 20 MW of RF power in TE_{01} mode and 1 MW in second harmonic TE_{02} mode. The analytical and simulated results are found to agree within 5 %. Both chapter 2 and 3 predicted second harmonic TE_{02} mode is most troublesome.

In Chapter 4, the output waveguide section of gyro-twystron was designed to suppress the second harmonic TE_{02} mode, and periodic dielectric loading was chosen as a distributed loss technique, which suppressed the second harmonic TE_{02} mode. A design procedure/methodology was developed, which includes linear theory, loss rate calculation, and start current analysis. The variation of axial and radial length of dielectric rings was done to maximise the RF power of PDL gyro-twystron. The different practical dielectric materials are investigated to determine the suitability as periodic rings, and BeO-SiC (60 % - 40 %) was chosen as dielectric rings in the present case. In the present work, periodic rings in the linear section were partly inserted into grooves of the cylindrical waveguide. The PIC simulation of PDL gyro-twystron predicted 25 MW of RF power with a gain of 25 dB and efficiency of 26 %.

In Chapter 5, the mathematical formalism of gyro-twystron was developed to investigate the multimode behaviour of beam wave interaction in PDL waveguide. For this study, the dielectric rings were fully inserted into grooves of the cylindrical waveguide to realise the practical dielectric-loaded linear waveguide structure. The numerical analysis predicted that the PDL RF structure could suppress the second harmonic TE_{02} mode as well as provides adequate growth to the operating mode TE_{01} mode. The analytical and simulation studies predicted an RF power of ~ 160 kW in second harmonic TE_{02} mode, which is well below the 1 MW of RF power predicted in the same mode in an unloaded gyro-twystron. In addition to the oscillations suppression capabilities, PDL gyro-twystron showed the significant enhancement in beam wave interaction efficiency and predicted an RF power of 25 MW. From the axial growth profile of TE_{01} mode, the thermal analysis of the last four dielectric rings has been done to investigate the thermal loss and its associated temperature rise. From the parametric analysis, it was found that the operation of PDL gyro-twystron was oscillation tolerant at higher beam current. The analytical and simulated results were found to be in good agreement with 5 %.

A performance enhancement study of gyro-twystron was made in Chapter 6. An intermediate cavity was introduced in a single cavity gyro-twystron to enhance the gain and efficiency. From the simulation results, it was observed that prebunched electron beam provides better growth and saturation of RF power in the short output waveguide section. The PIC simulation of two-cavity gyro-twystron has predicted ~30 MW of RF output power as compared to ~31 MW through analytical calculation. Further, the particle emitter and collector were designed to operate at a higher modulating voltage and depressed potential to improve the beam-wave interaction efficiency and total efficiency of gyro-twystron, respectively.

7.2 Limitations of the Present Work and Scope for Further Studies

The present thesis focuses on beam-wave interaction in RF structure of PDL gyro-twystron in addition to the design of various subassemblies including RF input coupler, window, particle emitter, and collector. To increase the energy transfer in the desired mode, RF wave propagation can be altered by introducing the various distributed dielectric loading techniques in the output waveguide section. The present beam wave interaction study is limited to fundamental beam mode harmonic. However, higher harmonic is a better alternative to increase the figure of merit (P/λ^2) of the MW class gyrotron amplifier. Second harmonic operation of gyro-twystron can increase the figure of merit; however, a stability study is needed as the higher harmonic operation is vulnerable to oscillations. Implementation of distributed loading to second harmonic gyro-twystron will be an extension of present work, in addition to the electromagnetic analysis.

In the present work, the optimized value of beam-velocity spread of 4 % was considered. The beam-wave interaction efficiency depends upon the quality of the electron beam and minimization of inevitable velocity spread is a challenge. Therefore, the helical waveguide as velocity spread tolerant interaction structure can be implemented as output section of gyro-twystron amplifier.

The present thesis was limited to the two-cavity prebunching section. significant improvement in the gain and efficiency of gyro-twystron with an introduction of an intermediate cavity motivates the further studies on multi-cavity megawatt-class Gyro-twystron to fulfil the demand of particle accelerators. For RADAR application, the bandwidth enhancement can be achieved in multi-cavity kW class gyro-twystron through the staggered tuning technique.