CHAPTER 7

SUMMARY, CONCLUSION, AND FUTURE SCOPE

7.1. Summary and Conclusion

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

7.1. Summary and Conclusion

In the present dissertation, the design and analytical investigations of single frequency as well tunable frequency gyrotron oscillators, a kind of fast wave device, operating in the millimeter and sub millimeter frequency regime, have been carried out. Design study of the gyrotron using tapered cylindrical type RF interaction structures operating for the single frequency, medium power level gyrotrons operating in whispering gallery mode and volumetric mode have been presented. The device designs for its electron-bean and RF-wave interaction performance as well as thermal effects have been studies through analysis and simulation. For the first time, we have used single simulation tool for the gyrotron beam wave interaction and thermal studies. We have also suggested modified device design to mitigate the thermo-mechanical effect and its effect on the device RF performance are investigated. Followed by, the design and analysis of post interaction cavity components, like, the nonlinear taper section, quasi optical mode launcher and the output RF windows for transmission of the generated power in the interaction cavity to output transmission system have been described. An afetrcavity interaction study for single frequency gyrotron oscillator has also been carried by considering uniform axial magnetic field profiles. In addition, the design and frequency tuning studies of low power, tunable frequency gyrotrons for DNP enhanced NMR spectroscopies with electrical and magnetic tunings have been described in detail. Necessary steps required for the device parameters selection, tapered cavity RF interaction structure design of the tunable frequency gyrotrons have been presented. Further, the RF window used for the tunable frequency RF extraction has also been discussed.

In Chapter 1, with the introduction of gyro-devices evolution and literature review of high and low power gyrotrons operating in the single frequency and tunable frequency, respectively. Operating principle, and sub-assemblies of the gyrotron oscillators have been presented. Thereafter, various output couplings used in the gyrotrons and their advantages as well challenges have been presented. The applications of various power level gyrotrons generating RF radiation at single and tunable frequencies are discussed. The motivation of the present research and the organization of the thesis are drawn at the end.

With the knowledge of the implementation of the radial output type couplings in high power, high frequency gyrotron oscillators, in Chapter 2, the components, i.e., quasi optical mode converters that are responsible down converting interaction mode into low free space Gaussian like mode TEM_{00} for radial output couplings have been presented. Starts with the brief theory for the representation of interaction cavity mode TE_{mn} into group of rays used for the design of the quasi optical launcher, a part of mode converter followed by various types of QOM converters, i.e., Vlasov type and Denisov type are discussed. The dimensions of the Vlasov launchers for the 95GHz, 100kW TE_{62} and $TE_{10,4}$ modes gyrotrons, a single frequency medium power level rating, to be presented in the Chapter 3 and 4 of this thesis are determined. Observing the limitations and design considerations of Vlasov type converters, in the present work, Denisov type launchers have been chosen for radial output couplings. A brief notes on the coupled mode theory used for the analysis of Denisov type launchers have also been presented.

Usually, the quasi optical mode converters used for the radial output couplings are designed and optimized by widely accepted commercial software's LOT and SURF3D developed Calabaza's Creek. Considering its unavailability with respect to cost with researcher, we developed our own numerical code in the Matlab domain based on the theories available in various literatures for the study of quasi optical launchers as of now. The code has been validated by calculating the mode variation profiles and the wall intensity field for the $TE_{22\ 6}$, 110GHz gyrotron developed by Blank (1994). Thereafter, the optimization of the Denisov launchers for the $TE_{10,4}$, 95GHz 100kW by inspecting the mode variation profiles along the launcher followed by wall field intensity profiles have been performed successfully, with ~ 99% accuracy.

Further in this Chapter 2, the analysis and design of single disc type output RF windows for various type of operating modes, i. e., TE_{mn}, TM_{mn} and TEM_{00} have been presented in detail. Then, considering several window materials, the RF window for $TE_{10,4-}$, 95GHz has been designed by inspecting the transmission and reflection characteristics versus frequency at various disc thicknesses.

By knowing the role of gyrotron oscillators in security applications as a potential RF source for active denial system applications that operates in W-band; in Chapter 3, design and analysis of a tapered cylindrical cavity gyrotron oscillator has been presented. Considering the operating mode $TE_{6,2}$ as well as beam parameters by VGB 8095 gyrotron, given by CPI, USA, the design and analysis of RF interaction structure has been presented. By solving the single mode Vlasov approximation equation, the suitable interaction cavity dimensions are obtained and verified with published data. Thereafter, for the interaction cavity combinations, using non-linear, time dependent multimode analysis reported by Fliflet *et al.*, widely accepted theory for the beam wave interaction studies of gyrotrons, a self-consistent code has been indigenously developed and used for the analytical study of the designed gyrotron. For the same beam and cavity combinations, using PIC solver code of Commercial "CST Studio Suite", the gyrotron model has been designed. The beam wave interactions are investigated for different combinations of input parameters by considering a uniform axial magnetic field profile. The generated RF power and efficiency curves of the designed interaction cavity are found in good agreement. In practical circumstances, the occurrence of velocity spreads in the beam as well beam misalignments are inevitable though in small amounts. Considering this, the beam wave interaction studies are carried out using 3D PIC simulation. It has also been observed that a small shift in the beam optical axis affects severally on the performance of the system and limits the margin of dimensional tolerances. By RF studies, the interaction cavity dimensions that are responsible for the growth of RF power with desire qualities of 100kW at 95GHz are determined and optimized. But, due to metallic nature of the cavity walls, the generated RF power leads ohmic losses in the structure that acts as heat load there by thermal effects that causes mechanical deformations of structure which plays critical role in the RF performance of device. Therefore, for the present medium power level, the thermo-mechanical effects and its effect on the RF performance are investigated considering the cavity material conductivity as 5.8e7 S/m (an ideal value). The thermo mechanical effects and design of optimized cooling system parameters are determined by COMSOL Multiphysics by providing the generated ohmic losses as heat load. For the present work, instead of allowing coolant with different velocities and temperatures on the outer walls, by varying convective heat transfer coefficient, and providing extended heat surfaces called fins over the middle section the cavity, the cooling system has been optimized. The required coolant parameters for achieving the optimized heat transfer coefficient are determined. The RF studies of interaction cavity after taking the optimized thermal system effects are studied and the variations in the RF performance are under tolerable limits of the design.

In Chapter 3, the RF simulation study using commercial 3D PIC code "CST Studio Suite" and thermo-mechanical studies using commercial PIC code "COMSOL Multiphysics" have been carried out. It has been observed that, the thermal effects due to ohmic losses limits the margins of cavity dimensions tolerances and that necessitates the presence of cooling maintenance system for the high power devices. As well as, the shifts in the electron beam, i. e., misalignment of the beam axis with respect to cavity axis, have also been found to limit the device performance. Since, the dimensional and beam radius variations are also get scales with operating modes, so lower order mode gives small margin of tolerances, even though mode like, $TE_{6,2}$ is widely used at 95GHz frequency for 100 kW gyrotron, but observing these effects, we wants to investigate the advantages as well as challenges by operating this specification gyrotron device in the higher order volumetric modes, which is so far not fully explored and reported in the published literature, at least not accessible to us.

Considering the challenges and issues related to thermo-mechanical deformations and misalignments, in Chapter 4, we designed, analyzed and simulated the same rating gyrotron device that operates in a relatively higher order mode $TE_{10,4}$- that allows a wide transverse dimensions thereby more relaxation regarding thermal issues as well as it could also be upgraded to higher power levels too. In the literature, Krishna *et al.* (2011), have started the mode selection and the analysis of RF interaction cavity in the absence of electron beam though not dealt with the beam-wave interaction studies that includes RF analysis and thermo-mechanical analysis as well the post interaction components, like, nonlinear taper, and RF window designs were not reported. Considering this gap, as well as the goals mentioned in Chapter 3, in the present work, the design, analysis and simulated the device and its RF interaction cavity that gives the desired power in the operating mode $TE_{10,4}$ and larger dimension relaxes the thermo-mechanical issues are presented.

After the RF interaction cavity design, to ensure stable device operation at the desired oscillation frequency, the beam wave interaction studies of the cavity by adding a raised cosine type non-linear taper (NLT) has been carried-out for the axial uniform magnetic profile. By extending the single mode Vlasov approximation equation, the suitable nonlinear taper section has been determined by inspecting the cold cavity RF field profile (in the beam absent condition). Then, the RF cavity and NLT section has been optimized through the beam wave interaction studies. Since, the time dependent multimode theory proposed by the Fliflet *et al.*, have been used so far considering the uniform section of the cavity with ideal Gaussian beam. In the present work, we extended it by incorporating the actual field profile and is calculated by solving the Vlasov approximation equation to the combined RF cavity and NLT geometry. For the same, using the PIC code of Commercial CST Studio Suite, the beam wave interaction simulations are carried out with uniform DC magnetic field profile. The analytical results calculated from the updated time dependent theory as well from the simulations are found in good agreement. Observing the beam wave interaction calculations after adding the NLT section, it is found that a less uptaper with longer NLT section results early growth of RF power. In addition, observing the effect of beam misalignments on the beam coupling to the TE_{mn} mode, the additional coupling term has been incorporated to the time dependent multimode theory that allows successfully, the effect of misalignments on the beam wave interactions. The analytical and the simulated results for various offset in the beam axis with respect to the cavity axis are calculated and both results are found in good agreement. And it was found that for $TE_{10,4}$ mode, the effect of beam widths on the RF performance are very much less compared to that for the $TE_{6,2,}$ 95GHz gyrotron design. Instead of performing the thermo-mechanical calculations using the code COMSOL Multiphysics, for the present case, the thermo-mechanical analysis has been carried using Steady state thermal solver as well Mechanical solver using single code, i.e., available in the CST Studio Suite. As we targeted at the start of this chapter, Chapter 4, it was found the amount of ohmic losses are very much less than that for the $TE_{6,2}$ mode design though the calculations are done by considering two different conductivities, and as well the design of thermal system requires heat transfer coefficient value of 2000 with cavity thickness of 5 mm with no cooling fins present, which can be achieved very easily. It has been found that the frequency deviation in the gyrotron oscillation frequency without any cooling system in the case of $TE_{10,4}$ mode gyrotron operation are within the operational limit of the device. Though to achieve the targeted power in the higher order mode, one needs to sacrifice with the device efficiency to some extent. However, in future, by upgrading the design to high power levels the compensation for the efficiency can be mitigated by no additional need of a thermal cooling system as well as less sensitivity to the electron beam misalignments and more geometrical tolerances.

With the knowledge of studies made and reported Chapters 3 and 4 of this dissertation, we shifted our research focus towards the design of low power tunable gyrotrons for the DNP enhanced NMR applications by operating the device in the higher order axial modes and are presented here in Chapter 5. Various tuning techniques used in gyrotrons are discussed. In the present work, we have described the design methodology and designed an RF interaction structure that is able to generate a minimum RF power of 20W over a band of 2.4GHz for $TE_{5,3}$, 263GHz gyrotron for the 400MHz DNP NMR spectroscopy applications. In order to operate the device in higher order axial mode, a longer length interaction cavity section are required that results a high quality factors at the same lowers the starts oscillation currents of the modes. Considering the operating mode $TE_{5,3,q}$ from the literature and the design and analysis of RF interaction cavity are presented. In this Chapter too, by allowing the actual field profiles calculated for the RF interaction cavity geometry from the Vlasov approximation for the high order axial modes, the time dependent multimode theory has been carried out at two beam currents 400mA and 20mA via electrical and magnetic tunings. It was found that the designed cavity is able to generate the RF power levels of >20 W over a band of 2.4GHz centered at 263GHz. Then considering a SiO2, as window material, a single disc type RF window for the tunable frequency range has been designed by allowing various disc thicknesses. Further. It was found that smaller disc thickness results good transmission and reflection characteristics versus frequencies, however in the present case disc thickness of 1.155 mm.

It has been seen and presented in Chapter 5 that longer integration cavities lower the start oscillation current of mode excitation as well allows the excitation of high order axial modes. An experimentally demonstrated low power tunable gyrotron operating in $TE_{0,3}$ at

140GHz, has been revisited and reported in Chapter 6 of this dissertation. Here, for this device, its beam wave interaction studies by time dependent analysis as well as simulation using PIC code of Commercial CST studio suite have been carried out. Later, keeping the same beam parameters, and tailoring the reported RF interaction cavity such that excitation of the higher order mode via magnetic tuning that results increment in the tuning bandwidth has been demonstrated. It was found that an increment of 400MHz of bandwidth via magnetic tuning can easily be achieved through such modifications in the device RF interaction cavity.

In the last chapter, Chapter 7, the work embodied in the present thesis are summarized and the significant conclusions are drawn from the major findings. The limitations of the present study are discussed pointing out the scope for the future work.

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

In the present work, the mirror section of the quasi optical mode converter is not studied analytically even though several theories are available to explore. But, one key way is by solving the Stratton Chu integrals for the calculation of radiated fields from the launcher on the mirrors, with the suitable numerical methods for fast and accurate calculations. Though the RF window has been designed, the cavity thickness and type of window material can be optimized furthermore by investigating the thermo mechanical behavior of the RF windows due to the losses resulted from the generated RF power propagation. However the time dependent multimode theory has been given for the tapered magnetic field type for the interaction cavity, since, we have extended it for the after cavity interaction studies by taking a uniform magnetic field profile, incorporating a magnetic field profile more accurate beam wave interactions can be achieved. As well, instead of single tuning techniques, the design can be investigated by allowing a hybrid tuning for the enhancement of tunable bandwidth.

As well by incorporating the PBG type interaction actions, the tunability of the device can be increased.