Chapter 1: Introduction and Literature Review

1.1 Background and Motivation

Gyrotron devices are engineered for millimetre wave RADARs, particle accelerators, plasma heating and nuclear researches. The popular application of gyrotron oscillator is the formation of artificial Sun on the Earth through the thermonuclear fusion reactor, while the gyrotron amplifiers (gyro-amplifiers) find applications in particle accelerators and RADAR. Despite several opportunities, many research fronts such as space exploration, particle physics, etc. are remained unexplored, as the requirement of high RF power generation at a higher frequency is a major challenge to vacuum electronics engineering.

Vacuum electron devices (VEDs) differ from solid-state devices (SSDs) by the nature of conduction/propagation of electrons in a medium. In SSDs, electrons are drifting in solid medium and collision of electrons cause heat generation in semiconductor while in VEDs high mobility electrons propagate in vacuum along the tube. The collision and heat generation are localized at the particle collector. With these properties, VEDs generate high power and sustain very high breakdown voltage as compared to SSDs. Despite the fabrication difficulties and considerable size, VEDs generates high power per unit volume as compared to SSDs. In VEDs, the particles are transferring their energy to RF wave. In the early days until 1960, most of the development studies of VEDs (conventional VEDs) are focused on Cherenkov and transition radiation-based devices. However, with increment in operating frequency, the realization/fabrication of conventional VED is difficult as the RF structure is in the order of wavelength. In case of slow-wave VEDs, beam interception near to the wall of RF interaction structure, where the slow waves are localized, limit the power handling capabilities. High power VEDs are needed to explore the microwave and millimetre wave regime and drive the research towards cyclotron resonance maser (CRM). The gyrotron devices overcome this limitation (dependency of transverse dimension over operating frequency) by employing CRM instability. The transverse electric (TE) field in RF structure perturbs the gyrating electrons, and relativistic dependence electron cyclotron frequency leads to the bunch formation. To transfer the electron energy to RF wave, the cyclotron frequency of electrons is kept smaller than the RF signal.

Development of megawatt-class gyrotron amplifier for particle accelerator application is needed to unlock the new possibilities in particle physics. In the large hadron collider (LHC) at CERN, Geneva, two powerful particle accelerators are employed to collide particles. Performance of vacuum amplifiers is evaluated by RF power and wavelength P/λ^{2}, *i.e.* figure of merit. Since the transverse dimension of conventional VEDs are in the order of wavelength, fabrication difficulties occur at higher frequencies as well as poor power handling capabilities limit their performance. Therefore, the fast wave gyrotron amplifiers including gyro-klystrons and gyro-twystrons are used as RF driver for a particle accelerator. Gyro-klystron amplifiers can generate megawatt level of RF power at higher frequency $f \geq 10$ GHz; however, high power operation of gyro-klystron amplifiers are susceptible to microwave breakdown. By employing a traveling wave output section, the gyro-twystron amplifier mitigates the problem of microwave breakdown and become more suitable for megawatt-class operation. A short output waveguide increased the suppression capabilities of parasitic modes as compared to gyro-TWT. With a hybrid interaction structure, gyro-twystron provides a significant gain-bandwidth improvement over gyro-klystron. However, the bandwidth improvement is insignificant for particle accelerator application.

1.2 Microwave Tubes Development

Before the discovery of electron by J. J. Thompson in 1897, Edison has observed the electric current between the filament and plates in the evacuated bulb in 1883. By exploiting this property, Fleming developed a vacuum diode in 1904, which was used for the detection of direct current. Later in 1906, Lee defrost introduced a grid to Fleming's valve and developed a triode. With further research and development efforts, these vacuum technologies were matured enough and became a backbone of Radio transmission during the World War I (WWI). Later on, these radio technologies are extended towards the detection/ranging, and pre-WWII pressure invoked the research on RADAR to detect the enemy flight, which needed a new generation of vacuum tubes. During WWII, magnetron became the core of the RADAR system, as well as the research efforts on VEDs, took out the linear beam devices such as klystrons and TWTs. In VEDs, electrons energy is transferred to the RF wave. The bunching of electron beam and its synchronism with the RF wave are identified as two essential phases in the energy exchange mechanism from electron beam to the RF wave. Figure 1.1 shows that the basic functioning block of microwave tubes. Electrons are emitted from the gun section interact with the RF wave in interaction structure and after transferring their energy, these electrons collide at the particle

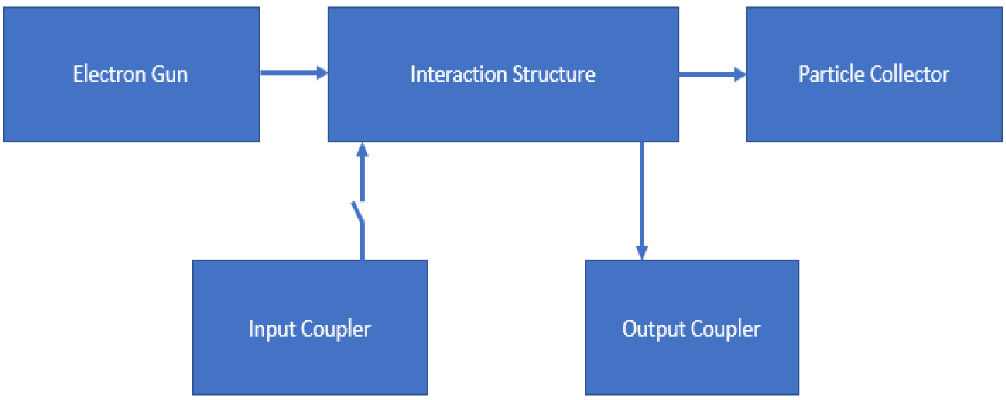

Figure 1.1 Block diagram of the microwave tube

collector. The amplified RF signal is extracted from the output coupler section; however, the input signal is applied for VED amplifiers only. Various mechanisms alter the propagation of RF wave and electron beam in order to couple electron's energy to the RF wave, which characterize and classify the microwave devices. Historical developments of VEDs are discussed below in a taxonomical way to understand the evolution of microwave tubes.

Based on the propagation of electron beam, microwave tubes are classified as linear beam and cross-field devices [1]. In linear beam tube, electron beam is propagating in the same direction to applied DC magnetic field as reflected from its name O-type (O is the French acronym of TPO standing for *tubes à propagation des on des*)[1-2]. This magnetic field is applied to focus the electron beam along the tube. Klystrons and TWTs are examples of linear beam devices. In O-type tubes, the kinetic energy of electrons is transferred to the RF wave. While in M-type tubes, potential energy is converted into RF energy [1]. The electric and magnetic fields are arranged perpendicular to each other and electron motion is perpendicular to both fields, as reflected from the name M-type (M is the French acronym of TPOM standing for *tubes à propagation des on des à champs magnetique)*. These tubes are also called as cross-field devices. Cross-field devices are known as more efficient as compared to linear beam devices. Magnetron oscillator, a most famous example of cross-field device, which was developed by A.W. Hull in 1921, and further modified by E. Habann and A. Zacek [3]. In addition to the electron beam propagation, microwave tubes are also classified by generated radiation [4]. The electrons are moving faster than the phase velocity in a medium having a refractive index ($n>1$) causes the Cherenkov radiation ($v>v_{ph}=c/n$). To achieve this condition, the phase velocity of RF is retarded by slow wave structure (SWS) below to the speed of electron called Smith Purcell/Cherenkov radiation [4-5]. TWT and BWO are examples of Smith

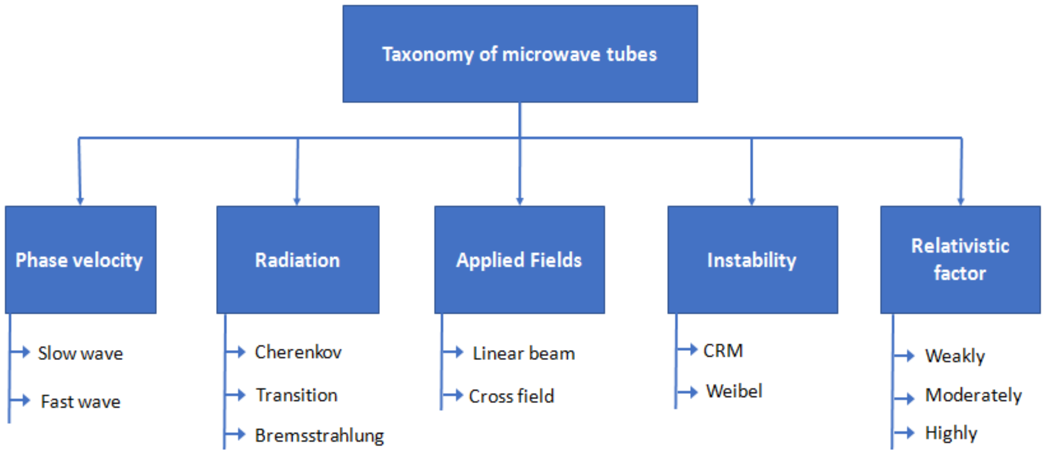

Figure 1.2 Taxonomy of microwave tubes

Purcell/Cherenkov devices. The electrons propagate through different media or motion of electrons are perturbed by grid type structures, causes the transition radiation [4]. Klystrons and Reltron are popular examples of transition radiation-based devices. Bremsstrahlung radiation occurs when electrons are propagating in magnetic field with an electric field or without the electric field. The synchronism between the operating frequency and cyclotron frequency ensures the beam-wave interaction for Bremsstrahlung radiation [4]. However, tailoring of RF propagation characteristics through the interaction structure is a prominent way to achieve the synchronism between RF wave and electron beam. Since the electron beam velocity cannot increase up to the speed of light, therefore, to obtain the synchronism between the electron beam and RF wave, slow wave structures are introduced in microwave tubes to reduce the phase velocity of RF below the speed of light. In the case of periodic slow wave structures the phase velocity is, $v_{ph}= (\omega/k_{zl}) <c$, *where* $k_{zl}=k_{zo}+2*l*pi/$d, and $(\omega/c) < k_{zl}$ gives the imaginary transverse wave number (k_{tl}). This shows the field of spatial harmonic exist near to the wall and to achieve better coupling of beam, which are positioned near to the wall of the tube [4]. The transverse dimension of the device in the order of wavelength, as well as beam-wave coupling near the wall of tubes limits the performance of slow wave devices at higher frequency. In fast wave devices, the electron beam interacts with RF signal in a smooth metallic waveguide. Gyrotron as fast wave device, overcome the limitation of power handling capabilities of slow wave devices. The electrons are gyrating under the constant magnetic field and periodic magnetic field in gyrotrons and FEL devices, respectively [4]. Beam wave interaction in FELs is governed by $k_w v_z = \Omega$, *where* $k_w = 2pi/\lambda_w$ and λ_w is period of wiggler magnetic field. Gyrotron devices overcome the dependency of transverse dimension using CRM instability and increase the power handling capabilities in millimetre and sub-millimetre range [6]. In CRM instability, the relativistic dependence of electron cyclotron frequency causes the azimuthal bunching [6]. The taxonomical description of microwave tubes is shown in Figure 1.2. Further, details of historical development and classification of microwave tubes (apart from gyrotron devices) are available in literature [1-4],[7], and the development of gyrotron devices are discussed in section 1.4. However, before the literature review of gyrotron devices including gyro-twystron, the physics of gyro-twystron amplifier is discussed in section 1.3, which includes the structural details and operating principle.

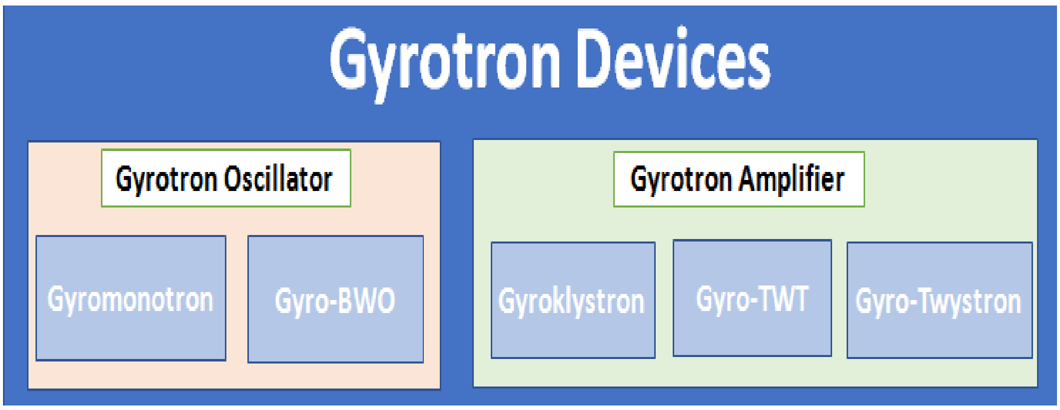

Figure 1.3 Variant of gyrotron devices

1.3 Gyro-twystron Amplifier: Structure and Physics

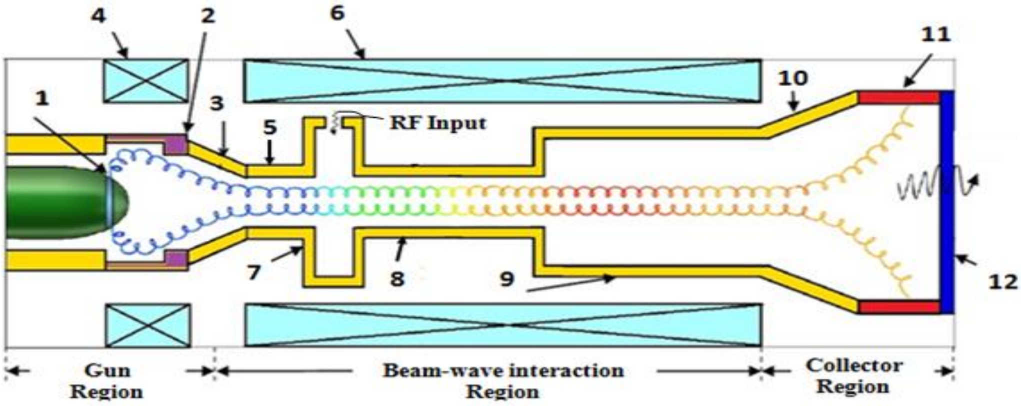

Figure 1.4 Schematic of gyro-twystron amplifier

Like the conventional twystron, the gyro-twystron is a hybrid amplifier and its RF interaction structure consists of one or more input cavities followed by an output waveguide as shown in Figure 1.4. To increases the gain of the amplifier, intermediate cavities are introduced. In multi-cavity gyro-twystron, the cavities are tuned at the different resonant frequency, *i.e.* stagger tuning, to increase the bandwidth [8]. To provide isolation, field-free drift tubes are employed between the adjacent cavities and the output waveguide section [9]. The gyro-twystron tube is an efficient high-power, microwave and millimeter wave coherent radiation amplifier, which is working on the principle of the cyclotron resonance maser (CRM) instability. The gyro-twystron amplifier has the potential to generate high powers over a wide range of frequencies in the millimeter and sub-millimeter wave band of the electromagnetic spectrum. With moderate power and moderate bandwidth, the gyro-twystron offers a viable solution for many millimeter wave radar systems. Like other gyro-amplifier, gyro-twystron consists of a magnetron injection gun (MIG), which produces an annular beam, an interaction region under the strong superconducting magnet, and an RF extraction region with the particle collector.

1.3.1 MIG and input coupler

The propagation of electron beam should support/synchronized with an EM wave and beam parameters should meet the design expectations of the RF interaction structure for the efficient beam wave interaction. At the interaction structure, beam parameters such as beam voltage, beam current, pitch factor, velocity spread, guiding centre radius and Larmor radius are chosen to maximize the beam-wave interaction efficiency [10]. The design of the MIG section brings these design parameters to interaction structure by optimizing magnetic compression ratio, down taper dimension, cathode slant and cathode-anode gap [10-11]. In MIG, the guiding centre radius is larger than the radius of Larmor orbit. Electrons are emitted from the cathode, which is generally temperature limited thermionic cathode, in which current variation is easily possible. MIGs are available in two major configurations, *i.e.* single and double anode configurations. The potential difference and gap between anode and cathode are varied to obtain the desired beam parameters. The transverse efficiency of gyrotron devices is directly proportional to the pitch factor. As the velocity spread increases with the pitch factor, the bandwidth of gyro-twystron is limited. The reasons are the space charge, initial thermal velocity spread, emitter roughness, and in-homogeneity of external fields in the region of emitters having a finite width[5].

In the case of gyro-amplifiers, an input coupler is employed to feed the input signal to RF interaction structures[12]. The RF signal is fed to the input cavity of gyro-twystron using a wrap-around coupler. The mode conversion mechanism and design methodology of an input coupler depend upon the rectangular waveguide's operating TE mode to circular cavity's operating TE mode. The RF window in the rectangular waveguide of wraparound coupler provides the vacuum sealing of the whole device [13].

1.3.2 RF Interaction region

The RF interaction structure of gyro-twystron amplifier consists of one or more cavities followed by an output waveguide. Cavities and waveguide are separated by field-free drift regions to provide the isolation between different sections. The electrons move towards the interaction circuit through a growing magnetic field. Due to adiabatic invariance of the magnetic momentum, the electron orbital momentum increases. The particles are interacting with the input RF electric field of circularly polarized TE_{mn} mode in the input cavity. The dimensions of cavities are chosen to resonate in the desired frequency and mode. The dielectric rings are introduced in the downstream of the cavity to lower the quality factor of the cavity. In the input cavity, the coupling slots are also reducing the quality factor. In addition to isolation between cavities and waveguide, the drift tubes provide the ballistic bunching [6]. Nonlinear beam-wave interaction takes place in the output waveguide section. Thus, the RF field developed at the output waveguide section is the amplified version of the applied RF field at the input cavity.

1.3.3 Output Section

The output system of gyro-twystron consists of an output taper, RF window, and particle collector. The design of output section depends upon the nature of output power extraction. In axial power extractions, an output taper, a particle collector, and an RF window are along the tube unlike the radial extraction output system, where a quasi-optical mode converter is placed between the output taper and particle collector. The output taper connects the interaction region to particle collector, and the magnetic field is tapered to diverge electrons to strike on the particle collector before the RF window. The radius transition in taper or taper profile is used to avoid the spurious mode oscillations and magnetic field is also profiled in such a way that no further interaction takes place in the output taper. In VEDs collisions of electrons is localized at the collector, hence increases the temperature at its surface. Therefore, an efficient cooling mechanism is needed. The depressed collector extract the energy of spent electron beam by applying an external applied electric field and improve the efficiency of gyro-twystron. Single stage depressed collector is preferred in the axial extraction output system as it is simple in structure and cooling. In the case of radial extraction of power, the regular waveguide section after the taper is transformed into a quasi-optical mode converter to convert the RF power in the waveguide mode to a Gaussian (TEM_{00}) free space mode followed by an appropriate mirror system for beam focusing and necessary phase corrections. The vacuum inside the tubes is maintained by RF window, which serves as an interface between the vacuum and the output transmission system. It should provide maximum transmission with minimum reflection as well as should possess good thermo-mechanical properties to support a high power operation. Based on these performance metrics, the material for an RF window is chosen.

1.3.4 Working Principle

The MIG generates an annular electron beam, which traverses through the down taper under the influence of increasing magnetic field to achieve the desired pitch factor at the interaction circuit. A pre-drift tube is employed between the down taper and interaction circuit to avoid the backward wave propagation towards the gun region. The RF input signal is fed to the input cavity of gyro-twystron amplifier using a wraparound coupler. RF signal perturbs the energy and phase of gyrating electron beam in the input cavity. These perturbed electrons are being ballistically bunched in the field free drift tube. In a multi cavity gyro-twystron, the subsequent action of perturbation and ballistic bunching occur in intermediate cavities and drift tubes, respectively. The quality of pre-bunched electron beam at the entrance of waveguide is measured by the bunching factor. These pre-bunching electron beams gyrating with cyclotron frequency that excites the RF wave in output waveguide. In a traveling wave section, the pre-bunched electron beam interacts with the growing RF wave and electrons are transferring their kinetic energy to the RF wave. In gyrotron devices, the energy is extracted from the transverse component of the electron and gyro-twystron can extract the energy from the both transverse and axial component of the electron. Energy extraction from transverse and axial components depends upon the beam velocity pitch factor and recoil parameter. The beam-wave interaction operation in the output waveguide is vulnerable to the oscillations occur at higher beam currents and pitch factor. The reflection from the output system also causes the instability using external feedback mechanism. After the interaction, particles and amplified RF wave propagated through an up taper without any mode conversion. The particles are colliding at the collector after transferring their kinetic energy to the RF wave, which is propagated towards/through RF window in axial extraction output system. In the radial extraction mechanism, a quasi-optical mode converter is employed between the up taper and particle collector. The beam wave interaction mechanism is discussed through the dispersion curve.

1.3.4.(a) Dispersion relation

The operating characteristic of gyro-twystron is discussed through the dispersion curve. The output waveguide section of gyro-twystron supports several transverse electric modes, which are represented by a waveguide mode equation, $\omega^2 = c^2\left(k_z^2 + k_{mn}^2\right)$, and gyrating electron beam are represented by a beam mode dispersion relation, $\omega - k_z v_z - s\Omega/\gamma = 0$. where, ω is the angular frequency of the RF wave, k_z is the axial propagation constant, s the harmonic number, γ the relativistic mass factor, and v_z is the axial electron beam velocity. In fast wave devices, the synchronism condition between the waveguide mode of RF wave and electron beam (fundamental or harmonic) can be obtained at the grazing intersection. In gyro-twystron, the beam mode line makes a tangent on the waveguide mode curve ($k_z>0$) at the operating point unlike in gyrotron oscillator ($k_z\sim0$). Figure 1.5 shows the fundamental harmonic beam mode line makes a tangent on the operating TE_{01} waveguide mode curve at an arbitrary frequency. Several interaction points including a tangent at the operating point is seen in the presence of several modes and other design issues are discussed through the dispersion curve.

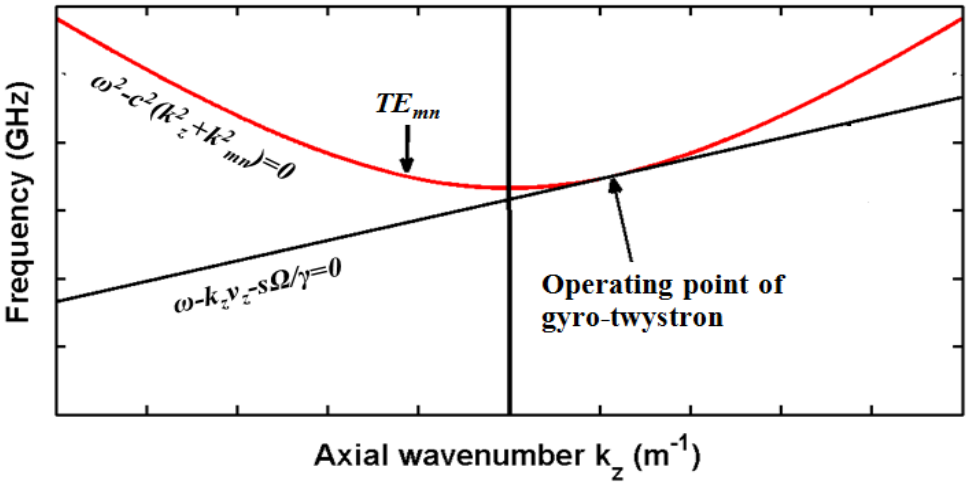

Figure 1.5 Dispersion diagram of gyro-twystron amplifier

1.3.4.(b) Cyclotron resonance maser instability

In the previous section, the numerical interpretation shows the synchronism between transverse electric waveguide modes and electron beam are depends upon cyclotron frequency and relativistic mass factor. The dependence of relativistic cyclotron frequency on electron energy is caused by CRM instability. The RF interaction structure supports several transverse electric modes, which interact with a gyrating electron beam under a constant magnetic field. Based on the phase of electric field and the motion of electrons, the relativistic cyclotron frequency is changed. The change in relativistic cyclotron frequency leads to the CRM instability and its mechanism can be understood from [14]

$$dw/dt = -e\left(v_t.E_t\right)$$

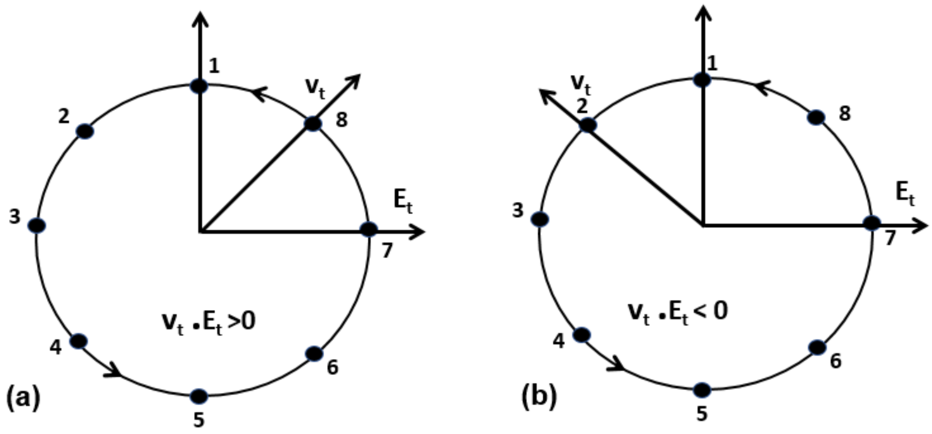

Figure 1.6 Cyclotron resonance maser mechanism

From Figure 1.6(a), it can be seen that in the right half of the circle $\left(v_t.E_t > 0\right)$, electron 8 is losing its energy and its relativistic mass is reduced. With lighter mass electrons are rotating faster. Similarly, From Figure 1.6(b), it can be seen that in the left half circle electron 2 $\left(v_t.E_t < 0\right)$ gained energy and became heavier. Cyclotron frequency of electron 2 is reduced. This increment and decrement of cyclotron frequency in the right half and left half, respectively, is relativistic dependence on electron energy, which further leads to the bunching.

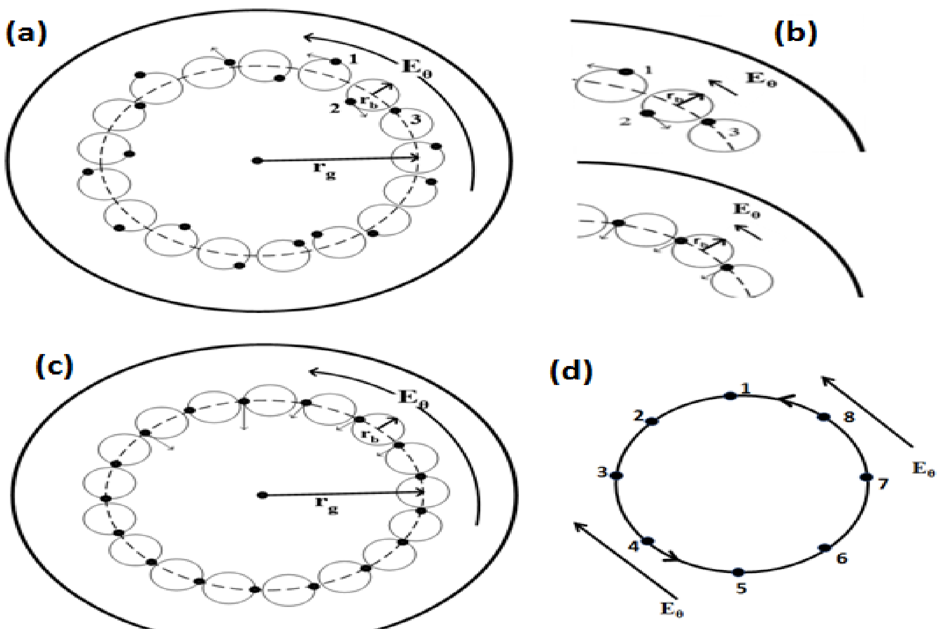

Figure 1.7 Phase bunching in cylindrical interaction structure

To understand the phase bunching process, axial velocity is considered as zero which deduce the beam mode dispersion equation to $\omega = s\Omega/\gamma$. MIG generates the annular electron beam having the radius of r_g and electrons are gyrating in their Larmor orbit having a radius of r_L under the influence of azimuthal electric field (E_θ), where ($r_g >> r_L$) as shown in Figure 1.7 (a). Eight electrons are distributed in Larmor orbit in a clockwise manner as shown in Figure 1.7 (d). The effective mass of electron 2, 3, and 4 is reduced, as they are losing their energy ($v_t. E_t > 0$) and their cyclotron frequency is increased. Similarly, the effective mass of electron 6, 7 and 8 is increased, as they are gaining energy and their cyclotron frequency is decreased. After the few cycles, electron formed a bunch in the Larmor orbit at the electron 1, *i.e.* orthogonal point of field and electron motion as shown in Figure 1.7(c). To extract the energy from electron, the RF frequency should be larger than the cyclotron frequency.

1.4 Literature review

1.4.1 Gyrotron devices

The discovery of CRM instability is ignited the research of fast wave devices. In late 1950, the discovery of CRM mechanism was made by Twiss [15], Gaponov [16], Schneider[17] and Zheleznyakov [18] that led to the development of CRM devices. An Australian astronomer Twiss suggested that population inversion and stimulated transition are the essential conditions for the instability of EM wave [15]. Schneider proposed the quantum mechanical approach of CRM for simulated emission in long interaction time [17]. Gaponov examined both classical and quantum mechanical approach and also considered the axial bunching in addition to orbital bunching [16]. In 1960, Ka-band CRM devices (trochotrons) had been developed which delivered ~1 kW of RF power with the efficiency of 10 %. The spread in axial velocity limited the performance of trochotrons. The TE mode at the cutoff frequency ($k_z=0$) mitigates the effect of axial velocity spread and interacts with the beam efficiently. In 1965, a second harmonic CRM monotron was developed that delivered ~190 W of RF power (CW), and A. L. Goldenberg named it gyrotron, at Saratov, Russia [19]. Later on, gyrotron achieved the efficiency of 50 % and 20 % for the fundamental and second harmonic, respectively [20].

To develop the thermonuclear fusion reactor, physicists were looking for microwave and millimeter RF sources for plasma heating and identified gyrotron as a suitable RF source for ECRH applications. Alikaev *et al.* have successfully demonstrated the plasma heating using gyrotron radiation with significant increment in plasma temperature [21]. With this motivation, V. A. Flygin with the collaboration of *Salut* developed a 40 kW gyrotron at 1 cm wavelength [22]. To increase the high-power handling capabilities, higher operating modes are chosen at which large transverse dimension of RF section of gyrotron is achieved at higher frequency. Gyrotrons operated at higher order axisymmetric mode are suffering from mode competitions [23]. The whispering gallery modes are preferred to develop high power gyrotrons at high frequency. For long pulse operation, waveguide and taper design excite the spurious mode, which limits the RF power conversion into Gaussian mode. The radial extraction of RF power using quasi-optical mode converters, mitigate the problem of spurious mode generation after the interaction cavity [6]. In-depth the physics and analysis of gyrotron have been discussed in the literature [6], [24].

The applications of gyrotron oscillators are limited to plasma and industrial heating and not suitable for RADAR and particle accelerator applications [4], [25], [26], [27], [28]. For RADAR and particle accelerator applications, gyrotron amplifiers such as gyro-klystron, gyro-TWT and gyro-twystron are employed. The analogy between slow-wave monotron and CRM monotron opened the door of a newer version of gyrotron devices, especially gyrotron amplifiers (gyro-amplifiers). The variant of gyrotron devices are shown in Figure 1.3. With the gyrotron development, the contemporary research on gyro-klystron at 10 and 28 GHz motivated the gyro-amplifiers research [4]. Most of the gyro-amplifiers for RADAR applications were developed in Ka- and W-bands, as the atmospheric window are present at 35 GHz and 94 GHz, respectively [25]. In 1994, an X-band gyro-klystron amplifier was developed at IAP, Russia that delivered 700 kW of RF power for continuous power operation [29]. A Ka-band gyro-klystron has delivered 258 kW of RF power in second harmonic TE_{02} mode, and its performance was limited by TE_{01} mode [30]. In USA, the research on gyro-klystrons at the NRL and University of Maryland was focused for RADAR and particle accelerator applications, respectively [27], [31-32]. For RADAR application, a C-band gyro-klystron was experimented to produce an output power of more than 50 kW with 25 % efficiency using three cavities. In the late 1990s, the NRL has designed and developed a gyro-klystron to achieve 200 kW of RF power at 35 GHz [12]. The two-cavity, three-cavity and four-cavity configurations of Ka-band gyro-klystrons for radar applications were developed at the NRL by Choi *et al.*, Calame *et al.*, and Garven *et al.*, respectively [12],[33-34]. A four cavity W-band gyro-klystron was developed at the NRL that produced an RF power of 67 kW with an efficiency of 28 % [35]. This gyro-klystron was commissioned in 94 GHz WARLOC radar [35]. In early 1990s, the research on gyro-klystron was started for the particle accelerator at the University of Maryland. However, the design methodologies and related issues were discussed in 1985 [36], [9]. A two-cavity X-band gyro-klystron has delivered 24 MW of RF power with the efficiency of 24 % [37]. With the introduction of an intermediate cavity in the existing X-band two cavity gyro-klystron, the significant improvement of RF power ~27 MW was achieved with an efficiency of 32 % and gain of

34 dB [38]. However, the output cavity of these MW gyro-klystrons were susceptible to microwave breakdown and these gyro-klystrons were having narrow bandwidth [32].

Like conventional TWT, its CRM counterpart provided large bandwidth and became a suitable amplifier for RADAR applications [25]. The research on Gyrotron Traveling Wave Tube (Gyro-TWT) amplifiers was first initiated in the early 1970s, mainly at the NRL. The first experimental gyro-TWT amplifier was reported in 1979 by Symons *et al.* at the *Varian Associates* [39]. It was designed for 5 GHz with circularly polarized TE_{11} as the desired mode. The output power was around 50 kW with a total beam efficiency ~17 % with 3-dB saturated bandwidth of approximately 6% [40]. Barnett *et al.* reported another experimental gyro-TWT amplifier operating at 35 GHz in 1981 with a gain of ~18 dB at 35 GHz, when driven by a 70 kV, 1 A electron beam having a tapered waveguide and TE_{01} as the desired mode [41].

The continuous interaction of beam and wave in a metallic waveguide causes the growth of operating mode and various parasitic modes. The growth of these modes leads to the mode competition and instability. The RF propagation engineering in the waveguide has been done to minimize mode competition problem and increases the stability. Several new types of interaction structures were studied and categorized as mode control, mode filter and dispersion control technology [42]. Initially Severs are introduced between the waveguide to reduces the oscillations [43]. However, oscillations in RF power were observed at high current, and distributed loss technique was employed to achieve the stability. The first advancement was the dielectric loaded structure which was presented by Leou *et al.* in 1992 [44]. The advantage was that it offered a high bandwidth but had the disadvantage of low efficiency. As compared to the uniform dielectric loading (UDL), the Periodic dielectric loading is more suitable for high power operation[42]. The photonic band gap (PBG) structures are employed as mode filter technology for low power operation [42]. The bandwidth of gyro-TWTs is limited by velocity spread, as they are operated at far from cut off ($k_z > 0$) [42]. A novel cylindrical waveguide with a helical corrugation at the inner surface was proposed for gyro-TWT by Denisov *et al.* [45] and achieved an output power of ~ 1 MW with 20 % efficiency for 200-kV, 25 A electron beam at *X*-band [45]. The use helically corrugated waveguide allowed a significant reduction in the sensitivity of the amplifier to electron's velocity spread and an increase in its frequency bandwidth. In 1999, Chu *et al.* have developed an ultra-high gain stable gyro-TWT amplifier using the distributed wall loss technique for suppressing spurious oscillations [46]. The losses are distributed over the linear section of RF interaction circuit. Similarly, sever is used in conventional TWT as lossy section to cut-off the path of the reflective feedback. In contrast to sever, the lossy interaction circuit is an integral part of the linear amplification stage. An experimental *Ka*-band gyro-TWT was analyzed and obtained ~ 93 kW of saturated peak power with ~27 % efficiency, 70 dB gain, and 3-dB saturated output power bandwidth 3 GHz [46]. A Ka-band gyro-TWT using PDL was developed at NRL by Calame *et al.* that delivered ~ 137 kW of RF output power with the gain-bandwidth product of 53.9dB-GHz [47]. In 2014, experimental works of PDL gyro-TWT was performed at the University of Electronic Science and Technology of China (UESTC), China in Ku-band and W-band. The Ku-band PDL gyro-TWT developed by Wang *et al.,* that delivered ~153 kW of RF output power with an efficiency of 20 % and gain of ~41 dB [48]. In 2014, Ran *et al.* have introduced the PDL in W-band gyro-TWT, that delivered more than 90 kW of RF output power for the range of 93-97GHz [49]. The stability analysis of Ka-band gyro-TWT suggested that TE_{01} mode of operation in a PDL waveguide behaves similar to TE_{01} operation in a lossy metal waveguide [50]. In 2009, Du *et al.* have reported the modal transition effect in a PDL waveguide through which the second harmonic TE_{02} mode is well suppressed and the majority of power confined in TE_{01} mode [51]. The detailed state of the art of gyrotron devices has been discussed by M. Petelin [26] and M. Thuum [52], furthermore the research evolution and progress of gyro-twystron amplifier has been discussed below.

1.4.2 Gyro-twystron

The structural reformation by rearrangement of cavity and waveguide section was motivated to achieve the optimum performance between klystron and TWT. In 1962, Lichtenberg *et al.* have developed a hybrid tube consist of pre-bunching cavities and output waveguide section i.e. twystron and demonstrated the significant improvement in efficiency. This hybrid twystron tube has increased the efficiency to 37 % as compared to 20 % efficiency of TWT [53].

Similarly, the performance enhancement of twystron has been done by *Varian Inc.* to achieve high output power and gain by introducing coupled cavity as pre-bunching section in S-band TWT (VA-125B). With the motivation of substantial performance improvement, several linear beam twystron tubes have been developed by Varian Inc., and this mature hybrid vacuum amplifier is employed in AN/TPS RADAR of USA AIR FORCE [54]. VA-145 series of S-band twystron delivered 2-7 MW of RF power with the bandwidth of 8 % [55-56] , and VA-915A twystron delivered 10 MW of RF power with a bandwidth of 500 MHz. The first developed gyrotron oscillator (gyro-monotron) was exposed to the research world in the fifth inter-university microwave electronics conference in 1966 at Saratov. Moreover, twystron tubes were got matured by efforts of Varian Inc. well before the development of gyrotron. The analogy between linear beam devices and CRM devices, unlock the idea of gyro-twystron [4].

In the 1970s, the theoretical attempts had been made to study the physics of CRM-twystron. In 1973, the axisymmetric version of CRM-twystron was termed as gyro-twystron by Bratman *et al.* [57]. In 1977, Moiseev has suggested that gyro-twystron is an efficient amplifier with tapered input and output section [58]. The bandwidth of CRM-twystron is limited by velocity spread, and the amplification band of CRM-twystron is independent of drive input power [58]. Moreover, the theoretical studies suggested that amplification band of CRM-twystron is dependent on the difference between the operating and cut-off frequencies of the output waveguide section [57-58].

In 1985,Tran *et al.* have developed a weakly relativistic theory of gyro-klystron that was extended to gyro-twystron formalism [59] by introducing an output waveguide section. The pre-bunching formalism of gyro-twystron is remained same as gyro-klystron and can be extended in case of multi-cavity gyro-twystron. Tran *et al.* have made the self-consistent analytical calculations of field profile and transverse efficiency in a small signal environment [59]. In 1992, the nonlinear theory of gyro travelling-wave amplifier (gyro-TWA) was extended over the generalized theory of gyro-twystron [60]. Nusinovich and Li have presented a generalized theory of relativistic gyro-twystron to study the energy modulation of relativistic electrons in the input cavity and their phase bunching in the drift space [61]. The large-signal operation in the output waveguide of gyro-twystron at both first and second harmonics has been studied at length to get high efficiency [61]. The efficiency of gyro-twystron using an output waveguide at frequencies not so far from cut-off is quite tolerant of electron velocity spread. This paper suggested that the optimization of recoil parameter increases the energy extraction from both the axial and transverse components of electron motion [61].

With the advent of theoretical research, an experimental effort on gyro-twystron was made in 1990s for particle accelerator and RADAR applications at the University of Maryland and NRL, USA, respectively. The first experimental X-band gyro-twystron was developed by Lathem *et al.* for particle accelerator application[62]. In 1993, the pre-experimental study of X-band gyro-twystron had been made to investigate the stability issues and optimize the operating parameters [63], [64]. Stability studies reported the significant efficiency degradation with the increasing reflections from the end and predicted that the operating mode saturated more rapidly at higher bunching parameter [63]. The operating points are found in the trade-off between maximum available energy and minimizing the deleterious effect of velocity spread [64]. Energy conversion from the transverse component of the electron beam is increased with the pitch factor, while the energy conversion from the axial component is increased with Doppler up shift. However, the deleterious effect of velocity spread is increased for Doppler up shifted operation of gyro-twystron [64]. The effect of velocity spread is offset by a large beam current [64].

In 1994, a single cavity gyro-twystron operating in TE_{01} mode was experimentally tested with 21 MW of RF output power, 22 % conversion efficiency, and 24 dB gain [62]. The experimental studies of gyro-twystron were performed in the gyro-klystron test feasibility at UMD, Maryland [37]. Further studies on experimental gyro-twystron were made to optimize the performance metrics as well as to investigate the effects of parasitic modes and velocity spread. By ignoring the parasitic TE_{11} mode, seven parameters including magnetic tapering, voltage, velocity spread, pitch factor, the radius of output waveguide, drift tube length and kick in the first cavity were optimized to maximize the performance of gyro-twystron amplifier [65]. This study suggested/predicted that with the advent of MIG, an electron beam with low spread enhances the beam-wave interaction efficiency and Doppler up shifted operation is realizable [65]. In the stability study, parasitic TE_{11} mode is incorporated to examine the performance of gyro-twystron amplifier [66]. The reflectivity of RF window limits the operation of gyro-twystron at high pitch factor; thus, the efficiency is reduced. To improve the figure of merit, the second harmonic gyro-twystron amplifier was developed by Lawson *et al.* in 1995 [67] that delivered 12 MW of RF power with an efficiency of 12 % and gain of 12 dB. The mode competition and oscillations in down taper region, next to the electron gun, limit the performance of second harmonic gyro-twystron [67]. Since these gyro-amplifiers were developed for particle accelerator applications, the bandwidth enhancement was not primary performance metrics [66].

Based on these theories mentioned above, the design methodology of C-band gyro-twystron has been developed/investigated by Malouf *et al.* and its numerical simulation predicted an output power of 60 kW with an efficiency of 22.5 % and gain of 22 dB [68]. Parametric analysis of C-band gyro-twystron has been suggested that the bandwidth is independent of the length of the drift tube; however, the efficiency and gain are increased with the length of the drift tube [68]. To demonstrate the larger bandwidth, a research group headed by Perry M. Malouf at the NRL were working on C-band gyro-twystron amplifier for RADAR applications [68-70]. The stagger tuned rectangular cavities are operating in TE_{111} mode along with the TE_{11} operated circular waveguide and providing homogeneity, two rectangular cavities are arranged in cross-field polarization [68-70]. In 1994, Nusinovich *et al.* have developed the mathematical model of beam-wave interaction in mixed geometry three stage gyro-twystron [69]. The experimental studies were made on the mixed geometry three stage gyro-twystron that delivered 46 kW of RF output power with an efficiency of 23 % and a gain of 37 dB [70] against the numerical prediction of 55 kW with a gain of 26 dB and a bandwidth of 6 % [69]. These studies predicted the significant improvement in the gain-bandwidth product as well as predicted transverse efficiency of gyro-twystron is close to the gyro-klystron near/below unity pitch factor [70]. In 1998, Perry M. Malouf and G. S. Nusinovich have patented the cross-polarized mixed geometry gyro-twystron amplifier [71].

Another attempt to examine the bandwidth capabilities of the gyro-twystron amplifier was made by Blank *et al.* at the NRL [72]. A time-dependent MAGYKL code was employed to design and investigated three different configurations of three stage gyro-twystron using the circular geometry both theoretically and experimentally [72]. For beam parameters of $I_b=1\ A$, $V_b\ =16\ kV$, X-band gyro-twystron delivered 4.4 kW of RF power with the bandwidth of 1.6 %, which is limited by velocity spread [72], however, for the low-velocity spread the bandwidth was limited by the quality factor of output waveguide [72]. This study also validated the developed design methodology and theory for the future development of gyro-twystron amplifier at higher frequencies.

The low attenuation at 35 GHz and 94 GHz forms the window for communication and attracts the development of high power gyrotron amplifier at 35 GHz and 94 GHz. The theoretical studies of 35 GHz multi-cavity gyro-twystron were made to examine the stability and performance at high value of beam velocity pitch factor [73]. All three TE_{111} operated cavities are staggered tuned to achieve the bandwidth of 0.7 GHz with a gain of 55 dB [73]. The numerical simulation of Ka-band gyro-twystron predicted an RF output power of 90 kW with an efficiency of 33 %, which was enhanced to 43 % using magnetic tapering at the later stage [73].

The linear and nonlinear theories of multi-cavity gyro-twystron were developed to examine the performance metrics such as gain and bandwidth [8], [74]. Analytical study of the multi-cavity gyro-twystron was made to optimize the gain and bandwidth for the maximum gain-bandwidth product. Studies suggested that bandwidth in two cavity pre-bunching section is 1.65 times larger than that in the case of one pre-bunching section [74]. The nonlinear formalism of multi-cavity staggered tuned gyro-twystron was developed using point gap model [8]. It is observed that above the value of optimal bunching parameter the bandwidth is decreased [8]. Both linear and nonlinear theories of staggered tuned gyro-twystron amplifier predicted that two pre-bunching cavities are preferred over the one pre-bunching cavities [8] ,[74].

A 94 GHz gyro-twystron was designed and developed by Blank *et al.* at the NRL [75]. This multi-cavity gyro-twystron delivered 50 kW of RF output power with an efficiency of 17.5 % and a bandwidth of 925 MHz [75]. With the small increment in the magnetic field, bandwidth was increased at the cost of RF power. The nonlinear code of W-band gyro-twystron predicted 80 kW of RF power with a velocity spread of 4% [75]. In 2002, a review on gyrotron amplifiers was made by Blank *et al.* and suggested that the gyro-twystron possesses highest power-bandwidth product of 46.3 kW-GHz [76]. With this superior capabilities' the gyro-twystron amplifier was later installed at RADAR site in 2007 [77].

In 2006, Ngogang *et al.* have investigated the effect of large amplitude signal on the relativistic electron beam for gyro-twystron and gyro-TWT amplifiers and overlapping of cyclotron resonance at different harmonics was observed [78]. Since the waves were excited at the output waveguide section by the pre-bunched electron beam, which carries the harmonics of signal frequency, therefore, the gyro-twystron operation is more susceptible to the overlapping of cyclotron harmonics. However, this study suggested that the overlapping of cyclotron harmonics is ineffective to device performances [78].

1.5 Advantages of Gyro-twystron over other Gyrotron Devices

Research efforts on gyro-klystron and gyro-TWT amplifiers had been made to improve their performances and the trade-off between performances was achieved with structural reformation that lead to the present status of gyro-twystron. As compared to gyro-klystron, short output waveguide section of gyro-twystron not only increases the bandwidth but also mitigates the problem of microwave breakdown. For megawatt class operation, the energy of the RF field is localized in the output waveguide of gyro-twystron may be much smaller than the microwave energy stored in the high-Q output cavity of gyro-klystron. Granatstein *et al.* have suggested that gyro-twystron is suitable for megawatt class of operation [32]. By employing a short output waveguide section, Gyro-twystron not only reduces the parasitic instabilities and spurious oscillations but also reduces the deleterious effect of velocity spread as compared to the gyro-TWT. The cavity and drift tube together provide a pre-bunched electron beam to the output waveguide and the pre-bunched electron beam excites the desired mode. The pre-bunched electron beam interaction with the RF wave causes the fast growth and saturation of RF power in the short output waveguide. The length of output waveguide is vital for the stable operation of gyro-twystron, as the starting current typically scales inversely with cube of the length. With the introduction of intermediate cavities in gyro-twystron, significant improvement in gain is achieved. Another advantage of multi cavity structure is bandwidth, which is achieved by tuning different cavities at different resonant frequencies, *i.e.* stagger tuning. Such a hybrid-type device is, apparently, capable of combining the merits of the gyro-klystron (high efficiency and gain) and gyro-TWT (large bandwidth) that makes gyro-twystron as a promising amplifier of coherent electromagnetic radiation.

As compared to gyro-klystron the significant improvement in the gain-bandwidth product of C-band gyro-twystron has been demonstrated at the NRL. Blank *et al.* had evaluated several W-band gyro-amplifiers for RADAR application, and gyro-twystron amplifier had achieved the highest power-bandwidth product of 46 kW-GHz. Thus, gyro-twystron amplifier is considered as the promising candidate for very high-power applications with moderate gain and bandwidth.

1.6 Applications of Gyro-twystron Amplifier

Initial development efforts of gyro-twystron amplifiers were made for two major applications in particle accelerators and RADAR. For RADAR applications, most of the design studies of gyro-twystron were made at the NRL, while the University of Maryland has experimentally investigated the capabilities of gyro-twystron for particle accelerator application [4],[25],[52]. With the high gain-bandwidth product and high power-bandwidth product, gyro-twystron finds potential application for the millimeter-wave radars in the Ka-band and W-band [25]. By reducing the microwave breakdown problem, the gyro-twystron amplifier become a more suitable candidate for particle accelerator applications [32]. Very few research and development efforts on gyro-twystron amplifier limit its claims to RADAR and particle accelerator, which are discussed in detail as below.

1.6.1 RADAR

In the 1960s, the Varian has developed several slow wave twystron tubes for RADAR applications. Twystron becomes a successful microwave tube, which commissioned in US AIR force RADAR in the 1960s. Performance and services of the twystron tube from the mid of Vietnam war to now proved it as the successful hybrid tube. Gyrotron amplifiers delivered high power in millimeter wave regime and preferred in RADAR applications as compare to gyrotron oscillators. The existence of absorption minima motivates the research and development of high-power microwave device for radar applications at 35 GHz, 94 GHz and 140 GHz, i.e. atmospheric window[25],[27]. After a decade of Sputnik launch, a space debris radar is needed to track the object, which can damage the man-made exploration object. Russian Scientist develops the RUZA radar system at 35 GHz for detecting and tracking of space object using two 550 kW gyroklystron [79]. A W-band cloud profiling RADAR is needed to understand the effect of global warming as the dynamics of clouds, precipitation mechanism, development of turbulence and storms are part of cloud profiling study [80]. A W-band WARLOC radar system is developed at NRL, the USA, which has multiple applications in a target recognition, low angle tracking and atmospheric researches[80]. A 94 GHz gyroklystron is employed as a transmitter in RADAR system which delivered 80 kW of RF power with an efficiency of 20% [81]. In 50 years of space technology advancement, space became crowded by satellites and to upgrade space surveillance RADAR, Haystack Ultra-wideband Satellite Imaging Radar (HUSIR) system is developed to achieve the accuracy up to 0.5mill degree using gyro-twystron [82]. A 94 GHz gyro-twystron employed in HUSIR system which delivers 50 kW of RF power with the significant power-bandwidth improvement of 46 kW-GHz[77],[83]. The above-mentioned literature suggested that gyro-twystron amplifier is potential VEDs for radar applications.

1.6.2 Particle accelerators

High RF power is needed to accelerate the particles in RF structures and in particle accelerators RF energy of VEDs are transferred to particles, opposite to international beam-wave interaction mechanism of VEDs[25],[27]. Particle accelerator with its variants, find application in particle and nuclear physics, material researches and industrial material processing[25].

To reduces the length and cost of the collider, University of Maryland developed a series of gyro-amplifiers in X- and Ku-band and evaluated these gyro-amplifiers by $A=(p*t/\lambda^2)$[32].Performance and cost of VEDs to collider is computed by Wilson design. The cost of collider depends upon the number of gyro-amplifiers and performance of gyro-amplifiers depends upon the accelerating gradient, total efficiency and voltage required to drive gyro-amplifier [32]. A two and three cavity gyro-klystron delivers 24 MW and 27 MW of RF power in TE_{01} mode at 9.88 GHz. Since the output cavity of gyroklystron is susceptible to the microwave breakdown, therefore gyro-twystron amplifier is preferred for Megawatt class operation. Gyro-twystron amplifier delivered 22 MW of RF power in TE_{01} mode at 9.88 GHz and its second harmonic counterpart delivers 12 MW of RF power in TE_{02} mode at 19.76 GHz [62], [67]. Performance of gyro-twystron tubes is limited by parasitic instabilities and spurious oscillations[67]. Later on, Wilson has predicted the design of 5 TeV and 15 TeV-collider at 34.3 GHz and 91.4 GHz, respectively. For 15 TeV collider, a frequency doubling gyro-klystron delivered 10 MW of RF power at 91.4 GHz[84]. In 2017, multi cavity Ka-band gyro-klystron was developed by Wang *et al.*, which produces 1.5 MW of RF power at 36 GHz[85]. Above-mentioned literatures suggested that megawatt class gyro-twystron is suitable candidate and competing with other gyrotron amplifiers for the particle accelerator application.

1.7 Problem Definition

Despite potential advantages of gyro-twystron over gyro-klystron and gyro-TWT, a few research efforts were made on gyro-twystron, and various issues are unaddressed. The problem of microwave breakdown of gyro-klystron is mitigated by replacing an output cavity to traveling wave section, and gyro-twystron became a preferable candidate for megawatt-class operation. However, with the output waveguide section, the gyro-twystron carries the limitation of gyro-TWT. The parasitic instabilities and backward wave oscillations limit the performances of gyro-twystron, especially at megawatt power operation. Backward wave oscillations in gyro-twystron are caused by an external and internal feedback mechanism. Reflections from the output waveguide end are accountable for external feedback driven instability. As the waveguide length is above the critical length, an absolute instability is caused that leads to the backward wave oscillations. The oscillations in RF power at high pitch factor ($\alpha > 1$) in gyro-twystron limits its orbital efficiency. A large amplitude RF input power fed to the input cavity that causes the overlapping of neighbouring cyclotron harmonics in the RF output power. Since mega-watt class of gyro-twystron is operated at high DC input power and RF input power, the suppression of BWO modes and neighbouring cyclotron harmonics is a challenging task. Most of the reported literature of gyro-twystron studies is focused on experimental results and various design issues of gyro-twystron remain unanswered. Therefore, theoretical investigations including design and simulation of gyro-twystron amplifier are indeed required.

1.8 Significance of the Present Work

The present work focus on design, stability analysis and simulation of X-band gyro-twystron amplifiers using the nonlinear theories and 3 D PIC simulation code CST studio suite. From the available literature of gyrotron amplifier, a design methodology is structured/formed which determines the interaction structure dimensions and beam parameters of gyro-twystron. With the design parameters, modelling is done which projects the 3D view of interaction structure and cold (in beam-absent condition) simulated components of interaction structure convey the RF wave propagation characteristics. Design, modelling, and simulation of subassemblies such as coupler and

RF window address the issue of incorporation with interaction structure. A detailed discussion of design, modelling and cold simulation of interaction structure of gyro-twystron will help the prospective researchers.

Analytical and PIC simulation study of gyro-twystron convey the nature of beam-wave interaction mechanism and computes the performance metrics. The analytical model of study incorporates the multimode computational capabilities and computes the competing modes in addition to operating mode. In present study, we have identified oscillations and parasitic instabilities due to the competing modes and to suppress the competing modes, stability and design study is made which rectify the oscillations in gyro-twystron amplifiers.

A multimode theory of PDL waveguide is developed using the transverse electric field configurations and the particle dynamics expressions in PDL waveguide. The growth and suppression of operating and parasitic modes, respectively, are described in detail that determines the output power and efficiency in the operating and parasitic modes of the gyro-twystron amplifier. This mathematical model of PDL gyro-twystron is validated with PIC simulation code CST particle studio. The generalized version of developed analysis investigates the effect of various parameters on the performance of hybrid gyro-amplifiers. Performance enhancement study by introducing an intermediate cavity to single cavity gyro-twystron predicts improvement in output RF power, gain and efficiency. Optimized Particle emitter and collector enhance the beam quality and total efficiency of gyro-twystron.

1.9 Outline of Thesis

To investigate and suppress the parasitic instabilities and spurious oscillations in megawatt class gyro-twystron amplifier, a series of studies has been carried out and discussed in the respective chapter of the present thesis. The present work includes the detailed design aspects, rigorous analysis, and vast simulation results to understand the beam-wave interaction mechanism in megawatt-class X-band gyro-twystron amplifier. The performance enhancement studies of the gyro-twystron are also presented.

In the present chapter, the development of the conventional microwave tubes is discussed in two phases in addition to the classification of microwave tubes. In the first phase, the developments of slow wave devices are discussed and their limitation has been reviewed. A development journey of gyrotron oscillator to gyro-twystron amplifier is discussed in the second phase. A literature survey on the principle and development status of Gyro-twystron amplifiers is made. As a result, gyro-twystron amplifier is found as a superior RF source for RADARs and particle accelerators applications over other gyro-amplifiers. The problems existing in the present state-of-the art of gyro-twystron amplifier are studied along with the solutions to overcome those problems. The present thesis is structured into seven chapters and chapter organization is given, as follows.

The theory of conventional gyro-twystron is present in chapter 2. The design methodology of conventional gyro-twystron is developed to calculate the RF dimension of each sub-section of gyro-twystron. The electron dynamics and wave equations in a hybrid interaction structure are discussed to study the beam-wave interaction behaviour. Nonlinear theory of gyro-twystron for the beam-wave interaction study is extended to multimode for identifying parasitic modes.

Chapter 3 deals with the electromagnetic simulation of an X-band gyro-twystron to study the 3D beam-wave interaction behaviour. The RF interaction structures are analyzed in electron beam absent and present conditions. The individual sub-assemblies of gyro-twystron are cold analyzed to ensure favourable propagation. CST particle studio calculates the trajectories of an electron beam using PIC solver and projects the 3-D distribution of electron beam. PIC solver calculates the RF power, efficiency; gain, frequency of operation, etc. and pictorial representation of bunching mechanism which demonstrate the physics of beam-wave interaction in hybrid RF structure. The 3D simulation results of RF propagation characteristics and beam-wave interaction study are discussed in detail as well as the PIC simulation results are benchmarked with the available published results.

In Chapter 4, the stability and design studies of an X-band gyro-twystron using a distributed loss technique at its output waveguide section are presented. The PDL in the output section of the gyro-twystron amplifier suppresses the self-generated backward-wave parasites including TE_{11}, TE_{21}, and second harmonic TE_{02} modes. These parasites are investigated using the small signal linear theory. The PDL technique improves not only the stability of the amplifier but also its gain. The loss rate of different modes of PDL waveguide is calculated and PDL waveguide is designed to stabilize the operation of gyro-twystron against parasites.

In Chapter 5, a megawatt class X-band gyro-twystron using periodically loaded alternate lossy dielectric and metal output waveguide section is studied for its beam-wave interaction behavior using a fully nonlinear, self-consistent, and multimode theory. The modeling of gyro-twystron including an input coupler and RF window has been done using CST Microwave studio. Design parameters of input coupler and RF window is cold simulated to ensure the favourable propagation characteristics. The nonlinear amplification of the desired mode, as well as its competing parasites modes, are investigated using multimode code to ensure the device stability and validated through the CST particle studio.

In chapter 6, the performance improvement studies of X-band gyro-twystron using an intermediate cavity is discussed. The design methodology of two cavity X-band gyro-twystron has been developed to study its beam wave interaction characteristics. With the drawn design parameters, modelling and cold analyses of two cavity gyro-twystron have been done. A particle emitter and collector is designed, and trajectory of electron beam is optimized using Egun software. From the simulation results, it is observed that prebunched electron beam provides better growth and saturation of RF power in the short waveguide section.

In Chapter 7, the works done in previous chapters are discussed to conclude the thesis, and the major findings are structured to form a conclusion. The limitations of the present study are discussed to bring out the possibilities for future work. The technical contribution of the present thesis would fill the research gap in gyro-twystron and address the operational issue of gyro-twystron development at a higher frequency.

1.10 Conclusion

In the present chapter, the overview of microwave tubes is given with their classifications. Developments of microwave tubes are discussed in two parts; (i) from conventional to CRM devices and (ii) from the CRM devices to gyro-twystron. Literature survey of microwave tubes reflects the evolution of gyro-twystron. Available Literature of the gyro-twystron amplifier is reviewed rigorously with their scope, limitation and performance enhancement schemes. The Physics and RF structure of gyro-twystron has been studied with the subassemblies and critical elements. Advantages of this hybrid gyro-amplifier have been discussed which leads to the different applications, and gyro-twystron is an attractive VED amplifier for RADAR and particle accelerator.