CHAPTER 1

INTRODUCTION

AND

LITERATURE SURVEY

1.1 Introduction

1.1.1 Literature review

1.1.2 National scenario

1.1.3 Application spectrum

1.2 Gyrotron Operation

1.2.1 Electron beam emission, transmission and collection

1.2.2 RF generation, propagation and extraction

1.2.3 Operating principle

1.3 Motivation and Objective

1.4 Plan and Scope

1.5 Conclusion

1.1 Introduction

Gyrotron is now matured as an established device for generating high power at the millimeter and sub-millimeter waves frequencies. Gyrotron and its family devices expanded the growth of applications of millimetre and sub-millimetre wave frequency ranges due to their high power and high efficiency capabilities. Gyrotrons are serving the global community through their wide ranging applications covering almost each and every aspect of human life. Microwave tubes are well known devices since start of the last century; however, the gyro-devices came into existence only in the later half.

Microwave tubes are used to generate or amplify high powers at the microwave and millimeter-wave frequency range. Popular microwave electron beam devices include, traveling wave tube (TWT), klystron, gyro-traveling wave tube (gyro-TWT), gyro-klystron, etc. as the amplifiers; while magnetron, backward wave oscillator (BWO), gyrotron, peniotron, vircator, etc. as the oscillators. All these microwave tubes have their distinct roles in the growth and advancement of communication, defence, security, cooking, plasma research, etc. There is no limit of application due to its capability for the continuous performance improvement in terms of power, frequency, efficiency, life, etc. and thus maintaining and continuing the major imprints even after the stiff competition from the counterpart solid state devices.

The microwave tubes, which are basically vacuum electron beam devices, are invented almost hundred years ago; however, its importance was felt for the first time during World War II, when magnetrons were extensively used in radar systems. Later on, other devices, like, klystron, traveling-wave tube (TWT), backward wave oscillator (BWO), crossed field amplifier (CFA), etc. were invented and used in other specific defence and communication systems [Beck (1958), Carter (1990), Chatterjee (1999), Chodorow *et al.* (1964), Collin (1966), Gandhi (1981), Gewartowski *et al.* (1965), Gilmour (1986), Hutter (1960), Liao (1985), Liao (1988), Sims *et al.* (1963), Sivan (1994), Van de Roer (1994)]. The growth of microwave tubes sustained related to their performance and this growth continues even today and is believed to do so even for years to come [Baird (1979), Staprans *et al.* (1973), Steyskal (1992), Symons *et al.* (1986), Symons (1998)].

The microwave tubes can be classified as the slow-wave and the fast-wave devices depending upon the beam-wave interaction mechanism. In the slow-wave microwave device, the

RF wave phase velocity is less than the velocity of light, in the direction of the propagation of the electron beam. While in case of the fast-wave devices, the RF wave phase velocity remains more than the velocity of light; is the main criteria for the beam-wave interaction. Microwave tubes operate on the mechanism of conversion of the spontaneous radiation from the individual electrons into the coherent radiation by bunching the electrons in proper phase with respect to the radio frequency (RF) wave through tuning of the electron beam, DC magnetic field and RF interaction structure parameters. The conventional microwave vacuum tubes, like, TWT and klystron (based on the Cherenkov and the transition radiations), are of the class of slow-wave devices (RF phase velocity < velocity of light in vacuum) whereas, the microwave tubes, like, gyrotron, gyro-TWT (based on the bremsstrahlung radiation), etc. are of the class of fast-wave devices (RF phase velocity > velocity of light in vacuum). The fundamental drawback of the Cherenkov and the transition radiation devices are their need for an RF circuit as a delay line which slows down the RF phase velocity below the velocity of light in the direction of the electron beam. The size of the RF circuit directly proportional to the radiation wavelength. The transverse cross section of the conventional slow-wave tubes also decrease with the operating frequency. Due to the size reduction of the interaction circuit of slow-wave devices, the power handling capability reduces drastically at the high frequencies. Therefore, in the microwave regime ranging from 3–30 GHz, the conventional microwave tubes, such as, klystrons, TWTs and BWOs and other slow-wave devices, are good options for employment in the system. But as the operating frequency increases, that is, wavelength shrinks, it becomes more and more difficult to fabricate and align the tiny fragile components; more importantly, their smaller size also limit the power and/or current densities before ohmic heating and/or arcing result in failure of the device. As a result, such slow-wave devices are limited upto microwave frequencies.

Gyrotrons, or electron cyclotron masers, are better device selections for the higher range of the microwave regime due to their inherent capabilities of having the larger dimensions because of their lesser dependence on both frequency and operating mode. The gyrotron oscillator, sometimes referred to as "electron cyclotron resonance maser", is a high-power, high-frequency source of coherent electromagnetic radiations and can generate megawatts of RF power at the millimeter and sub-millimeter wavelengths with efficiencies as high as 60% [Edgecomb *et al.* (1993)]. The name now refers to a class of devices includes both oscillator and amplifier. Gyrotron is basically fast-wave microwave tube, which radiates millimeter and sub-millimeter waves by bunching electrons (having velocities required for resonance conditions) with cyclotron motion under the influence of the strong DC magnetic field.

Gyrotron tube consists of an electron gun to generate an annular electron beam which is focused into an open RF cavity resonator along an axial DC magnetic field, created by a superconducting magnet. In the cavity, the RF field interacts with the cyclotron motion of the electrons in the beam and converts their transverse kinetic energy into the RF wave which may then be internally converted into a Gaussian beam. The spent electron beam leaves the cavity and propagates to the collector where it is collected. Fig. 1.1 shows the schematic of a gyrotron having the axial power output arrangement.

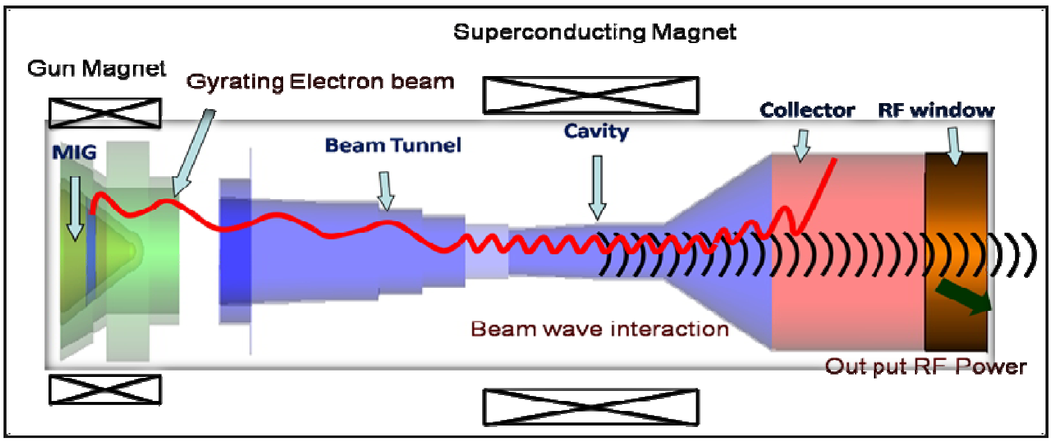


Fig. 1.1: Schematic of a gyrotron with axial power output [Singh (2012)].

1.1.1 Literature review

Slow-wave microwave tubes, as discussed earlier, came into industrial production line from the start of the last century and presenting their distinct roles in various applications. Moreover, in the second half of the last century, a new direction came into picture through theoretical research by Twiss in Australia, J. Schneider in US and Gapanov in USSR (now Russia) [Gaponov (1959), Schneider (1959), Twiss (1958)]. These works culminated in a new type of microwave tube, known as the fast-wave microwave tube. The generation of RF was made possible through interaction between the fast RF wave and helically gyrating electron beam; and thus gyrotron device came into existence. The development of the gyrotron was made by Gapanov and Kisel at Radio-physical Research Institute, Gorki, USSR [Gaponov *et al.* (1967), Flyagin *et al.* (1988), Nusinovich *et al.* (1999), Nusinovich (2004)].

After initial development of gyrotron, more experimental work were focused on the gyrotron developments at different power levels and higher harmonics. In the whole decades of 1970's and 1980's, very progressive work in the theoretical as well as the experimental area have been carried out on the gyrotrons and other gyro-devices, like, gyro-klystron, gyro-TWT, etc. The main motive of these work were to improve the device efficiency with high output power. The research work on gyrotron development were also started at Brazil, Korea and Germany in the late 1980's and early 1990's. After then new devices, such as, megawatt gyrotron, co-axial cavity gyrotrons and terahertz gyrotrons were developed in 1990's and early 2000's [Choi *et al.* (2005), Dammertz *et al.* (2000), Dumbrajs *et al.* (2004), Glyavin *et al.* (2007), Idehara *et al.* (2008), Idehara *et al.* (2010), Kasugai *et al.* (2005), Neilson (2006), Rzesnicki *et al.* (2009), Thumm (2009), Watanabe *et al.* (2007)]. During 1990's and early 2000's, the most impressive progress was demonstrated by the gyrotron research team of the FZK, in Germany, where this work was done as an International Thermonuclear Experimental Reactor (ITER) task in European Fusion Development Agreement (EDFA) cooperation between FZK Karlsruhe and HUT Helsinki. Work on co-axial gyrotrons also continued independently in Russia, U.S.A., Brazil, and Japan [Felch (1990), Kimura (1997)]. Piosczyk (2005), Piosczyk (2007), Thumm (2010)]. In this way, the device development spans all over the world. At present, the progress in gyrotron is remarkable with almost reaching 1-2 MW power levels at 140 GHz and 170 GHz, respectively, for plasma research and upto THz with moderate power for nuclear spectroscopy applications through the technological breakthroughs and use of new materials [Barker *et al.* (2005), Borie (1991). Dumbrajs *et al.* (2004), Idehara (2008), Sakamoto *et al.* (2009), Thumm (1998), Thumm *et al.* (2005), Thumm (2006)]. The present status of the gyrotron tube along with the progress in the development of the tube at the various Institutes in the globe with the detail specifications is described by Manfred Thumm [Thumm (2009)]. Fig. 1.2 shows some recently developed gyrotrons [Idehara *et al.* (2010), Thumm (2010), Rzesnicki *et al.* (2009)].

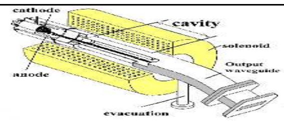
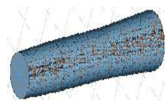
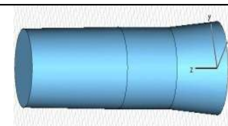
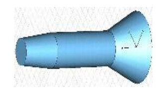
India is working in the field of slow-wave microwave tubes, such as, magnetron, klystron, traveling-wave tube, etc. since last fifty years but the work in the area of fast-wave microwave tubes, namely, gyrotron and gyro-devices was started mostly in the last decade on device development level. The extensive R&D work on the different frequency and power levels gyrotrons started at the CSIR-Central Electronics Engineering Research Institute (CEERI), Pilani. A lot of efforts were attempted with an aim to establish the indigenous design and development technology of gyrotron at CEERI [Singh *et al.* (2010), Singh *et al.* (2011), Alaria, Bhomia *et al.* (2011), Alaria, Mukherjee *et al.* (2011), Kumar *et al.* (2011), Kumar, Singh, Kumar, Khatun *et al.* (2011), Kumar, Singh, Kumar, Sinha (2011), Kumar, Singh, Kumar, Khatun *et al.* (2011), Yadav *et al.* (2011), Kumar, Goswami *et al.* (2011), Kumar, Singh, Singh, Sinha (2011), Kumar, Singh, Kumar, Bhattacharya *et al.* (2012), Khatun *et al.* (2012), Singh *et al.* (2012), Singh, Kumar, Sinha (2012)]. The work on gyrotron development at CEERI, Pilani was initiated for its potential use in the plasma fusion tokamak systems ADITYA and SST-1, ongoing ITER project and upcoming ITER-India activity.

(a) (b) (c)

Fig. 1.2: Typical high power gyrotrons : (a) 170 GHz, 1 MW gyrotron for ITER (Japan), (b) 140 GHz, 1 MW gyrotron for WX-7 (FZK), (c) 0.259-THz gyrotron for DNP-NMR spectroscopy [Barker *et al.* (2005), Borie (1991). Dumbrajs *et al.* (2004), Idehara (2008), Sakamoto *et al.* (2009), Thumm (1998), Thumm (2005), Thumm (2006)].

It is of interest to have a look into the growth of gyrotron since its inception. Presently gyrotron development touches megawatts power and terahertz frequency levels. Table 1.1 presents a typical growth picture of gyrotron, which clearly shows that there is quantum jump in the gyrotron performance in terms of output power from 6W to megawatt, operational frequency from 8GHz to tera-hertz, operating mode property from simple rectangular TE_{10} mode to high volume $TE_{28, 8}$ mode, magnetic field strength from 0.3T to 20T, gyrotron window using simple mica to CVD diamond and so on to so forth.

Table 1.1: Typical Gyrotron Growth Profile

Parameter	**8.8 GHz**	**42 GHz**	**140 GHz**	**1 THz**
Cavity				
Mode	TE_{101}	$TE_{0,3}$	$TE_{28,8}$	$TE_{4,12}$
O/P Power	6W	200 kW	970kW (~1 MW)	350 W
Beam parameter	10kV/ 100mA	65kV/ 10A	75kV/ 40A	30kV/ 200mA
Gun Type	MIG(Glass Triode)	MIG	MIG	MIG
Collector	Rectangular	Circular	Circular	Circular
Window	Mica type	sapphire	CVD diamond	Boron nitride
Tube length	0.6 m	2.0 m	3.5 m	2.5m
Magnetic field	0.3 T	1.65	5.0 T	20T
RF collection	Axial	Axial	Quasi-optical	Axial
Cavity	Rectangular	Circular	Circular	Circular
Institute	Gorki, Russia	CEERI, Pilani	FZK, Germany	Fukui, Japan

1.1.2 National scenario

Gyrotron is presently an established oscillator in microwave and millimeter wave regime. Its development may be divided mainly into two regions, covering medium power and very high power regimes. Medium power millimeter to sub-millimeter wave gyrotrons are required for ceramic sintering plasma scattering measurements, and more recently electron spin resonance (ESR) experiments and nuclear magnetic resonance (NMR) signal enhancement by dynamic nuclear polarization (DNP) [Becerra *et al.* (1993), Becerra *et al.* (1995), Bykov *et al.* (1995), Gerfen *et al.* (1995), Hall *et al.* (1997), Kreischer *et al.* (1999), Mitsudo *et al.* (2000), Weis *et al.* (1999), Saito *et al.* (1985)]. While, high power millimeter wave gyrotrons are required as the power sources of electron cyclotron resonance heating (ECRH) of plasmas, electron cyclotron current drive (ECCD) of tokamaks, etc. [Callis *et al.* (2004), Eaves *et al.* (1997), Feinstein *et al.* (1987), Felch *et al.* (1990), Grantstein *et al.* (1987), Joseph *et al.* (2008), Kimura (1997), Nguyen *et al.* (2001), Piosczyk (2005), Popov *et al.* (2010)].

The gyrotrons and related gyro-devices are under active research throughout the world covering USA, Russia, European Union, Australia, China, South Korea, Japan, etc. Now, India through CEERI has also entered into this field of gyrotron on device development level in the last decade. It is of interest to mention that although the gyrotron research is growing globally due to its distinct potential capability of applications in various fields, like, plasma, material, security, spectroscopy, etc., particularly in high frequency and high power ranges. However, its application in future energy generation through the latest and very ambitious international project ITER (International Thermonuclear Experimental Reactor) program has enhanced the interest to a new level. ITER is a global program in which USA, Russia, European Union, China, Japan, South Korea and India are global partners. ITER is mainly aimed to create the facility to produce electricity from fusion power with an aim to solve the problem of future energy generation to a great extent.

India is a member of ITER project and IPR-Gandhinagar, India is already using low power commercial gyrotrons of CPI, US and GYCOM, Russia in their tokamak systems. Considering the indigenous plasma fusion tokamak systems ADITYA and SST-1, ongoing ITER project and upcoming ITER-India activity, the extensive work on the design and development of different frequencies and power levels gyrotrons is started at CEERI, Pilani for having indigenous gyrotron for future use in Indian Tokamak system. Due to all these applications, two activities were initiated at CEERI for the potential use of gyrotron in the plasma fusion technology. Presently, three projects are in progress at CSIR-CEERI, namely, (i) "Design and Development of 200kW, 42GHz CW/Long Pulse Gyrotron" a multi-institutional project, funded by Department of Science and Technology (DST), New Delhi, (ii) "Design and Development of High Frequency (120GHz), High Power (1MW) Gyrotron" and (iii) "Design and Development of short pulse 1MW, 170GHz gyrotron" funded by Council of Scientific and Industrial Research (CSIR), under CSIR-Network scheme. The first Indian gyrotron, that is, 42GHz, 200kW gyrotron would be used in Indian tokamak system. And, the research around 120GHz and 170GHz gyrotrons would a beginning in the field of megawatt gyrotrons. In India, the research activities around such type of devices are still limited in few institutes only, namely, CEERI-

Pilani, IIT(BHU)-Varanasi, IPR-Gandhinagar, IIT-Roorkee, SAMEER-Mumbai, MTRDC-Bangalore and DAV-Indore while the device is globally getting popularity due to its capability to generate very high power radiation in millimeter and sub-millimeter wave range.

1.1.3 Application spectrum

The application spectrum of gyrotron is wide and covers wide aspect of present requirement as an efficient and stable high power millimeter and sub millimeter wave source though its spectral quality is poor. Some of the applications may be referred to scientific applications covering particle accelerators to thermonuclear plasma fusion devices and plasma diagnostics, strategic applications covering radar to missile guidance, industrial applications from cooking to material processing and ceramic sintering, medical applications through spectroscopy, etc. Typical applications of gyrotrons are discussed in the following paragraphs.

Strategic application: An active denial system (ADS) system developed by Raytheon for the US Air Force Research Labs is a non lethal, counter-personnel, directed energy weapon system and can be used against human targets at a distance beyond the effective range of small arms. Thus, a focused millimeter wave energy beam produced by an ADS induces intolerable heating sensation on a human skin causing the individual to be repelled without injury [Gaponov *et al.* (1994), Liebe (1989)]. ADS could be used to stop, deter and repel hostile elements without application of lethal force. 95 GHz millimeter wave radiation is used in the ADS because of the natural atmospheric window at this frequency [Neilson *et al.* (2009)]. This system can focus the 95GHz millimeter wave effectively upto few kilometers. Another advantage of 95GHz frequency is its small skin depth compared to the other commercial microwave frequencies, like, 2.45GHz or 915MHz. The radiation can reach upto 1/64th inch only in the human skin and create burning sensation. The blood vessels and nerve system are located beneath this skin depth and thus this radiation is found to be not harmful.

The high power millimeter wave are also used for the various kind of atmospheric diagnosis, like, cloud monitoring, measurement of humidity, turbulence structure determination, etc. [Hermitte (1987)]. Rather than the cloud monitoring, the millimeter wave technology can also used for the various other atmospheric diagnosis, like, detection of turbulence structure, relative humidity, etc. [Manheimer (1992)]. The gyrotron oscillator of 183GHz frequency can be used in humidity detection because the water absorption rate is maximum at this frequency. The air turbulence is the major cause of air accidents. The radar system working at the atmospheric window frequencies of 35GHz and 94GHz frequency can be used for air turbulence detection. The THz radiations can penetrate through the several kinds of non-conducting and non-polar materials, like, cloth, papers, wood, etc. and can be used for the security systems. The THz radiations can also be used for the determination of water percentage.

Scientific application: Presently, the main thrust for the research and development of the gyrotron is linked with the need of high power, high frequency electromagnetic wave source for the magnetically confined plasma fusion research, mainly for electron cyclotron resonance heating (ECRH). Around the world, gyrotrons of a wide range of frequencies are in use in the tokamak systems for generation of magnetically confined plasmas. The interest in gyrotron research has shown a quantum jump with the launch of ITER program which is aimed to generate energy in present 21st century through controlled nuclear fusion process in the magnetic confined plasma for generation of electricity. ITER is the biggest plasma fusion machine under construction at Cederach, France with the global participation. It is planned to use 170GHz gyrotron with 1-2 MW of output power in the ITER for ECRH and ECDD (Electron Cyclotron Current Drive). High efficiency, high output power and long pulse width are the key requirements for the development of the fusion gyrotrons.

Further, the remote detection of the radioactive materials through THz radiation is a new finding and this can be achieved through 670GHz gyrotron [Nusinovich *et al.* (2010)]. The real benefit of THz radiation in remote radioactive material detection lies in property of its focusing property in a beam of small cross section area as well as the breakdown mechanism in the radioactive material.

Industrial application: Microwave / millimeter wave heating is basically dielectric heating in which the radiations between the frequencies ranges from 300MHz to 300GHz can be easily used. The utilization of microwaves for heat generation was accidentally discovered during the testing of magnetrons at the Microwave and Power Tube Division of Raytheon in 1950. In the early 1950’s, the first industrial microwave oven for heating the food was developed [Link *et al.* (1999)]. The use of microwave has been adopted for several industrial heating applications, like, rubber technology, ceramic sintering, chemical processing, composite fabrication, food processing, etc. [EPRI (1993)]. The use of millimeter wave in the heating for ceramic sintering, pharmaceutics and other material processing was started in the late1980 [Link *et al.* (1999), Miyake (2003)]. Apart from heating and sintering of ceramics, millimeter wave heating is also used for the surface hardening, drying, removal of the organic binders and moistures from the surface, growth of nanostructure ceramics, etc. The gyrotron oscillators are capable to deliver hundreds of kilowatt to few megawatt of output power at the millimeter wave range. Gyrotron can be installed along with the applicator easily and can operate with good stability in output power and frequency. The gyrotron oscillators are adopted as a millimeter wave source for the industrial heating applications and this field of application opens the way of development of new kind of gyrotron devices which would be compatible for the industrial use. The first use of the gyrotron oscillator in the millimeter wave sintering was demonstrated at Oak Ridge National Laboratory in 1980 [Kimrey *et al.* (1987)] The remarkable work on the application of gyrotron in the millimeter heating was done in Osaka University, IAP Nizny Novogrod and Oak Ridge National Laboratory [Hirotaa *et al.* (2004)].

Mainly, the gyrotrons of the frequency range 20GHz to 35GHz are used for the industrial applications [Felich *et al.* (1999), Hirotaa *et al.* (2004), Link *et al.* (1999), Makino *et al.* (2001), Thumm (2000)]. The RF heating mechanism of the ceramics and other dielectric materials directly depends on the frequency of the radiation. So, in case of high frequency RF energy, sample size becomes very small. The low frequency gyrotrons are suitable for heating purpose.

Medical application: Electromagnetic spectrum ranged from 300GHz to 3THz is called sub-millimeter-wave radiation or simply THz radiation. The major areas of applications of THz gyrotrons are dynamic nuclear polarization (DNP), electron spin resonance (ESR), solid state nuclear magnetic resonance (NMR) spectroscopy, etc. Further, THz radiation is non-ionizing due to small energy of photon and does not damage the tissues and DNA unlike X-ray. THz radiation shows unique spectral properties for several materials and used in the form of time domain spectroscopy. In the medical science and structural biology, THz radiation sources emerged as a key component in the form of DNP/ ESR/ NMR spectroscopy [Bajaj *et al.* (2007), Tatsukawa *et al.* (1995)].

1.2 Gyrotron Operation

The gyrotron operation defines the process of RF energy growth caused by the transfer of electron beam energy and is based on the conversion of electron beam energy into coherent electromagnetic radiation. The gyrating electron beam is generated by an electron beam source advances towards the interaction structure under the influence of continuous growing magnetic field in a direction perpendicular to the electric field to reach maxima of the RF electric field with the minimum beam radius for the beam-wave interaction. This external DC magnetic field is produced using a superconducting magnet, located at the center of the RF interaction cavity causes the electrons to gyrate at the cyclotron frequency. The magnetic field in the interaction region is tuned in such a way that this cyclotron frequency or one of its harmonics is close to the frequency of RF radiation. The following sections the electron beam formation, RF generation mechanism, propagation and extraction of RF wave along with the basic principle of gyrotron operation is briefly described.

1.2.1 Electron beam emission, transmission and collection

The electrons emitted from the cathode forms an electron beam and a system which produces electron beam of desired electrical parameter and cross section is called as electron gun. The electron gun used in a gyrotron is usually a magnetron injection gun (MIG), so-named as it resembles a magnetron assembly. The conical shaped cathode emits gyrating electron beams with the electrons having small cyclotron orbits under the influence of a magnetic field, as required for the cyclotron resonance condition [Baird *et al.* (1986)]. In an electron gun, the electrons are emitted from the cathode forms an electron beam of suitable parameters, namely, beam diameter, beam perveance, beam density, etc. and pass through the region for interaction with the RF wave. This is true for the gyrating electron beam in a gyrotron too. However, the beam-wave interaction in a gyrotron, the transverse electron energy is needed and thus the velocity ratio of the electrons between their transverse velocity and the axial velocity is another important parameter in a MIG.

The electron beam emitted from the conical shaped cathode in a MIG, works on the principle of thermionic emission, which is based on the heating of an emitting surface to allow electrons to overcome the work function and escape upto the surface. The commonly used thermionic emitters are tungsten, LaB_6 cathodes, oxide cathodes, dispenser cathodes, scandate cathodes and thorium-based cathodes. Present days, dispenser type of cathode is usually preferred due its high emission current density, life, and reliability [Sabchevski *et al.* (2008)].

After transfer of the transverse kinetic energy of the electrons to the RF field for effective RF power growth in the RF interaction structure, the spent gyrating electron beam advances further towards a sub-assembly known as beam collector for the final collection. It is of interest to mention that there are two types of gyrotron based on their RF collection mechanism, known as the axial output gyrotron having the same propagation axes for the RF and the electron beam and the radial output gyrotron having the perpendicular axes for the RF and the electron beam [Thumm (2010)]. In between interaction structure and collector, the gyrating electron beam travels through a subassemblies, such as, nonlinear taper and quasi-optical launcher in the radial output gyrotron. The electron beam and RF propagation in an axial type of gyrotron under development at CEERI is schematically shown in Fig. 1.1.

Collector of the gyrotron, as mentioned earlier, is employed to collect the unspent electron beam. The energy of electrons after participating in the interaction process is dissipated on the walls of the collecting surface of the microwave tubes including gyrotron. At the collector the electron beam can be collected at a reduced potential, thereby saving of DC electrical energy. Thus, the collector is one of the major components of gyrotron to collect the spent electron beam and dissipate it in the form of heat efficiently. If there is no collector in the tube then after passing through the interaction region and transferring energy to the output RF beam there is no region for collecting spent electrons and the gyrotron ultimately fails to operate. Therefore, clearly, for the effective as well as efficient operation of the gyrotron, one needs an energy recovery system known as the collector.

1.2.2 RF generation, propagation and extraction

The RF interaction structure in a gyrotron is usually an open ended RF cavity and in this structure region an effective interaction between the gyrating electron beam and the TE mode RF wave present there takes place. The gyrotron RF interaction cavity is usually a three-section cylindrical structure as shown in Fig. 1.3 where the sections are known as input taper, mid uniform active and output taper sections [Whaley *et al.* (1994)]. The first input taper section is tapered in its radius and designed in such way that its radius is continuously decreasing to cut-off point so that it behaves as a cut-off section for the operating RF mode and attenuates the back propagation of RF power towards the electron gun side. The uniform cylindrical middle section is the main beam-wave interaction region where the required RF power growth due to an effective electron beam and RF wave interaction. This RF interaction circuit can support several electromagnetic modes simultaneously. The RF fields in this region interact with the orbital electron beam kinetic energy for generation of RF output [Alaria *et al.* (2011)]. The third section is the output taper section having increasing radius taper profile and used for the conversion of standing wave into the traveling wave as well as to stop the further RF signal growth in this region so that RF power radiation can be transmitted out to the next section of the device facilitating the further growth of RF signal. For example, in an axial type of gyrotron, the generated RF power in the interaction cavity propagates towards RF window mounted along the gyrotron axis after passing through nonlinear taper and collector sections. While, in a radial type of gyrotron, the RF power is collected through gyrotron window mounted perpendicular to gyrotron axis after passing through quasi-optical mode converter system.

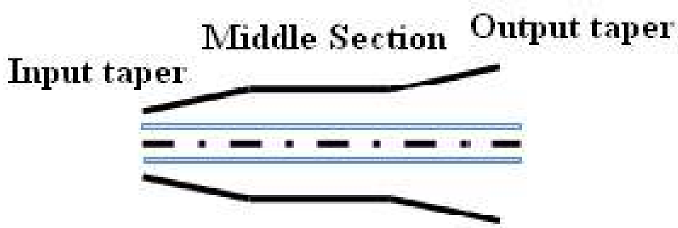


Fig.1.3: Gyrotron interaction structure

In the quasi-optical RF output system, several methods, based upon the optical phenomena, are utilized to couple out and transform the RF power generated in the interaction cavity of the device operating in the higher order mode into Gaussian type of the RF signal. The quasi-optical output system has two main functions [Vlasov *et al.* (1988)]. The first function is to separate the spent electron beam and the generated RF power. The second most important function is to convert the high order cavity mode into one or more linearly polarized paraxial RF beams for the effective radial exit through one or more output windows.

A quasi-optical mode converter is the combination of an open waveguide (launcher) and a mirror system [Neilson (2006)]. The waveguide constitutes either a simple cut Vlasov or helical cut Vlasov or rippled wall Denisov type launcher that directs the microwave energy radially through a wall aperture, separating it from the spent electron beam [Denisov *et al.* (1992), Lorbeck *et al.* (1995), Vlasov *et al.* (1975)]. The radiated wave is then focused by a series of reflectors that also serve to guide the microwave beam through a low loss vacuum window and then out of the tube. The internal mode converter reflectors must be properly shaped to provide a field profile at the window that accommodates the thermal properties of the window material and minimizes edge losses.

In the gyrotron oscillator, ceramic RF window is used as the vacuum seal for the tube and also serves as an RF exit outlet, that is, extraction aperture for the RF output power from it. Obviously, the gyrotron window must be made of a low loss ceramic material, which is also suitable for ultra high vacuum application. The conditions for oscillations in the interaction cavity especially the mode competition problems are dependent on the reflections from the window. Because of the high power, the thermal management of the output window becomes an important aspect. The design as well as the choice of the working temperature of the window has to be carefully chosen. Edge cooling does not seem to be sufficient even for medium power gyrotron at room temperature. Face cooling is much more efficient, but it requires a double discs window [Haldeman (2001), Heidinger *et al.* (2002)].

1.2.3 Operating principle

It is always preferable and helpful to revisit the RF growth mechanism in a gyrotron oscillator for its better understanding, design and development. This is evidently possible through the resonance between the electron cyclotron frequency and the operational frequency of a gyrotron. Keeping this aspect into consideration, the following section briefly elaborates analytical RF power generation mechanism in a fast wave CRM interaction based device, like, gyrotron.

The electron beam gyrates under the influence of the DC magnetic field governed by Lorentz force and very clearly, the electron cyclotron frequency (Ω_c) can be easily written as [Baird (1979), Nusinovich (1999), Nusinovich *et al.* (1999), Nusinovich (2004)]:

$$\Omega_c = \frac{eB_0}{m_0\gamma_0} \tag{1.1}$$

where B_0 is the DC magnetic field at the RF interaction cavity region, e is the electronic charge, m_o is the rest mass of electron, and γ_o is the relativistic mass factor. The electron beam and RF wave interaction produces angular velocity modulation of the electrons, which in turn produces the modulation of the electron energy. This phenomenon can lead towards the electron bunching of the beam. To achieve such a mechanism, a resonance condition must be satisfied between the periodic motion of electrons and the electromagnetic wave in the interaction region represented as [Baird (1979), Nusinovich (1999), Nusinovich *et al.* (1999), Nusinovich (2004)]:

$$\omega - k_z v_z = s\Omega_c \tag{1.2}$$

where ω is the wave angular frequency, k_z is the characteristic axial wave number, v_z is the electron axial velocity or electron drift velocity and s is the harmonic number, respectively. For case of gyro-devices, e.g., gyrotron, v_z is always kept much smaller with respect to the value of $v_\perp$ (transverse velocity of the electrons) and thus the Doppler shift term equal to $k_z v_z$ becomes very small and thus (1.2) becomes:

$$\omega \approx s\Omega_c \quad . \tag{1.3}$$

The helically gyrating electron beam produced by the magnetron injection gun (MIG) interacts with the electromagnetic field (in the $TE_{m,n}$ mode) of the same frequency as of the cyclotron frequency, when the electron beam passes through the RF interaction region. This causes bunching of the electron beam. The dispersion diagram (ω versus k_z plot) indicates a resonance of the beam with the cavity mode as an intersection of the waveguide mode dispersion curve (hyperbola) which may be obtained through the expression given as [Baird (1979) , Nusinovich (1999), Nusinovich *et al.* (1999), Nusinovich (2004)]:

$$\omega^2 = k_z^2 c^2 + k_\perp^2 c^2 \quad , \tag{1.4}$$

where $k_\perp$ is the characteristic transverse wave. The beam-wave resonance line (straight line) can be obtained through (1.2). In case of a device with cylindrical resonator, the transverse wave number may be defined as :

$$k_\perp = \chi'_{m,n} / r_o \quad , \tag{1.5}$$

where $\chi'_{m,n}$ is the m^{th} root of the corresponding Bessel function ($TM_{m,n}$) or derivative ($TE_{m,n}$) and r_o is the waveguide radius, respectively. Phase velocity synchronism of the two waves is desired in the intersection region. The dispersion diagram for the gyrotron interaction for fundamental resonance can be represented as shown in Fig. 1.4. While, Fig. 1.5 shows the dispersion characteristics of the gyrotron interaction structure, usually cylindrical cavity, for the harmonic operation of the device. Fig. 1.5 clearly shows that the interaction points between the beam line of the electron cyclotron harmonic mode and the dispersion curve of the waveguide mode represented, respectively, as the straight lines for the electron cyclotron harmonic modes (for *s* = 1, 2, 3, ...) obtained from (1.2) and the parabolic curve obtained from (1.4).

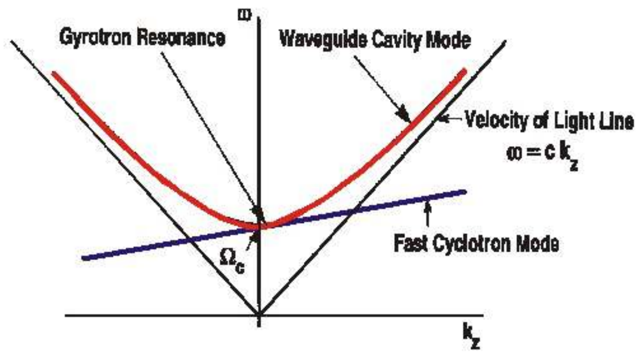


Fig. 1.4: Dispersion diagram for the gyrotron fundamental interaction [Nusinovich (2004)].

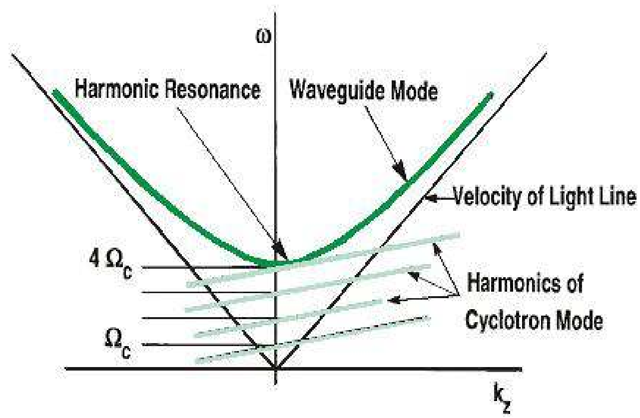


Fig. 1.5: Dispersion diagram for the gyrotron harmonic interaction [Nusinovich (2004)].

1.3 Motivation and Objective

Gyrotrons are proven device for the high power generation at the millimeter and sub-millimeter waves with good efficiency and stability for their use in various applications, like, industrial heating, plasma heating in magnetic confinement fusion experiments, radars, communications, driving accelerators, etc. [Felch (1999)]. Significant improvement in the device performance has also been achieved in the recent past for both pulse as well as CW operation [Thumm (2010)]. However, in our country, so far development has not been picked-up for this class of devices.

The development for a high power millimeter wave device, like, gyrotron requires various steps, processes, technologies and its standardization related to the design, development, testing, etc. As such, this is a new activity in our country and therefore, all these steps are essential and require the detailed studies. No doubt, some information and data are available in the literatures particularly in design and testing aspects but not complete in true sense, that is, these can be not be used directly without developing our own technology and expertise. Moreover, almost no clear and reliable information are available in public domain related to the development of the gyrotron components as well as the complete device. Therefore, the objective of the present study is very clearly defined around the establishment of the indigenous design, development and testing skill and knowledge around the actual gyrotron device assemblies, like, MIG electron gun, RF cavity and collector of the 42 GHz, 200 kW gyrotron to be developed. So the present study is planned to be centered around the 42 GHz, 200 kW gyrotron development which can be directly linked with the gyrotron indigenous development, particularly for the MIG electron gun, RF interaction cavity and collector assembly of the gyrotron. For this purpose, the available information is properly tuned and then combined with the commercially available software to successfully establish an in-house detailed design steps for the various components. The facilities for the development and testing of gyrotron components have been created. It is worthy to mention that the objective of the thesis, that is, design and development of gyrotron electron gun-collector module and RF interaction structure is to be successfully completed through design, development and testing. In this process, obviously, some more intermediate development technology and information will also be added to the scientific community, particularly for the gyrotron developers and researchers.

1.4 Plan and Scope

Gyrotron is already identified as a lead device for high power millimeter wave generation and our county, India, requires these devices for its potential use in the plasma fusion tokamak systems, ongoing ITER project and upcoming ITER-India activities apart from the DRDO needs. In India, we are engaged in the R&D of slow-wave devices since last more than five decades but the work in the area of fast-wave microwave tubes, namely, gyrotron and gyro-devices was started mostly in the last decade on device development level. A lot of efforts are needed to establish the indigenous design and development technology of gyrotron in the country since it is closely guarded strategic area. With this in a view, a 42GHz 200kW CW gyrotron development work has been taken up in the country under multi-Institutional mode where both CSIR-CEERI and IIT(BHU) are the partners. For this gyrotron, its different assemblies design, development, characterization and process standardization have kept the plan of the present research. This gyrotron research work is reported here in the form of the thesis which is outlined in seven chapters, Chapter 1to Chapter 7.

Evidently, Chapter 1 is an introduction of the theme and starts with discussion related to the gyrotron. Since, gyrotron comes under the spectrum of the fast-wave microwave tubs and thus, microwave tube is introduced with some examples of slow-wave microwave tubes too. The history, limitation and need of both slow-wave and fast-wave microwave tubes along with the difference in between to be presented. Gyrotron growth profile from its inception around 1960 to the present scenario related to global and nation levels is also briefly discussed. Further, the performance enhancement of a device is directly related to the device application and thus the application spectrum of gyrotron has to be elaborated. Gyrotron operation needs electron beam and RF; and thus their generation, transmission, extraction/ collection are briefly presented. For basic understanding of gyrotron operation, the basic principle of gyrotron operation is also presented. Finally, the objective and outline of the thesis are discussed.

Chapter 2 of the present thesis elaborates the study of the gyrotron electron beam source, that is, the magnetron injection gun (MIG) for use in the 42 GHz, 200 kW gyrotron. At first, the various steps, analytical design equations and design parameter range needed for the design of MIG are to be presented and then synthesis is needed to be carried out to estimate the basic parameters of the electron beam and the MIG electrodes, such as, cathode and anode. Gyrating electron beam trajectory analysis is also needs to be carried-out for the final design of the MIG. The study of the practical problem of the electron beam misalignment adds new but an important information for the fabrication and stability of MIG and thus also needs to elaborated carefully and in detail. The MIG mainly consists of two subassemblies: cathode-heater assembly for obtaining electron beam emission and anode-cathode system for accelerating the emitted electron beam towards the interaction region of the device. The cathode heater subassembly responsible for the good uniform emission of the electrons responsible for the proper functioning of the MIG.

The cathode-heater subassembly is used in the MIG of the gyrotron. Its design, development and characterization will be described in Chapter 3. The heater is used for heating the cathode surface which basically acts as the electrons emitter. MIG cathode is a conical ring shaped structure which helps in formation of a helically gyrating annular electron beam and works under the temperature limited condition. The dispenser cathode is usually used in the gyrotron MIG and a toroidal shaped heater is used on its back to uniformly heat the entire cathode surface. The design study of cathode-heater assembly is critically carried-out and elaborated in this Chapter 3. The developed cathode-heater assembly is described in Section 3.3. Further, the developed cathode-heater assembly will be tested to determine the cathode surface temperature independently in a bell jar system and also in the complete magnetron injection gun (MIG) assembly. In MIG system, the cathode-heater subassembly is first to be vacuum processed and then characterized under practical situations.

The gyrotron cavity is the region where the electron beam and RF wave interaction takes place in the gyrotron. Thus, the design, development and RF characterization of the RF interaction cavity is an important activity for the development of an efficient gyrotron oscillator and is to be covered in Chapter 4. The design steps covers the various steps, such as, the synthesis for the basic estimation of cavity parameters, the nonlinear theory for the estimation of output RF power, beam-wave interaction simulation for the final designed cavity and the related parametric studies, etc. The RF measurement methods for the cavity performance are also discussed with the non-destructive experimental characterization of the fabricated gyrotron cavity.

Chapter 5 is devoted to the design and analytical studies of the collector of the gyrotron device which is used in the final stage of the device to collect the spent electron beam. The collector is supposed to dissipate the energy of the spent electron beam, due to conversion of the kinetic energy into the thermal energy, leads to temperature increase of the collector assembly. Therefore, the collector design should be such that there is not much rise in the collector temperature. Hence obviously, the collector design covers various steps, like, preliminary dimensional and surface design, electron trajectory analysis and thermal analysis. For this purpose, a simple undepressed type test collector for use in “MIG-collector module” is selected in the present work.

The development and characterization of a gyrotron gun-collector module is an important step towards device development. The gun-collector module is basically an assembly of the gyrotron gun, that is, magnetron injection gun (MIG) and a test collector. The assembly is purposely integrated with aim to test the performance of MIG in a best possible manner as the vacuum can be easily created inside a closed system having MIG. The designs of the piece-parts of MIG are completed with the help of synthesis and electron beam trajectory analysis (Chapter 2) and the cathode-heater assembly in Chapter 3 of this thesis. The materials used to fabricate MIG are molybdenum, monel and high voltage ceramics. The development of gun-collector module is discussed in Section 6.2 and the characterization of magnetron injection gun is also carried out and described in Section 6.3. The successful fabrication of "MIG-collector module" for 42 GHz, 200 KW gyrotron is noteworthy. Its successful implementation with testing will also be presented in Chapter 6 covering the engineering designs and then fabrications of piece-parts as well as assembly processes. Then the final integration, the vacuum processing, the high voltage testing and the beam emission testing is to be presented.

Finally, Chapter 7 summarizes the results achieved in Chapters 1-6 for a brief overview of the study carried out during Ph. D. dissertation. The limitation and future scope of the study have also been discussed.

1.5 Conclusion

In the present chapter, the work embodied in the present thesis is outlined. The basics of conventional microwave tubes along with the gyrotron oscillators have been briefly discussed. The major applications of gyrotrons, with a peered literature review of the gyrotron have been presented. Brief outlines of the state-of-the-art, improvement and advancement of the gyrotron have been given. An overview with the discussions regarding the need, motivation, plan and scope of the present research work is also presented.