CHAPTER 2

INTRODUCTION TO GYRO-DEVICES

In the past few decades, there has been considerable effort to provide coherent, high-power sources in the electromagnetic spectrum. Among many of these devices, gyrotrons have proven to be efficient sources for r.f. generation at high power levels and up to very high frequencies. The applications for gyrotrons range from microwave sources for industry, medicine, high power radar, plasma diagnostics, material sintering, to r.f. driver for high average power accelerators. The main motivation for the development of high frequency and high power gyrotrons is that some applications such as magnetic heating require frequency range above 100 GHz and with power in excess of several hundred kilowatts.

The advantage of high average power capability of gyrotrons is particularly evident in the millimeter wave region. Conventional devices such as magnetrons and slow wave devices such as klystrons, traveling wave tubes (TWTs) require structures smaller than the wavelength, and are prone to overheating or breakdown at high frequencies. Thus in this part of the electromagnetic spectrum they are severely limited in both power and efficiency.

Fast wave Gyro Devices are relatively new comers to the Microwave Family [36-48]. Also known as “electron cyclotron masers”, “cyclotron resonance masers” or simply “gyrotrons”, gyro devices take advantage of cyclotron resonance condition to transfer energy from an electron beam to electromagnetic wave. The microwave frequency of the device and dc magnetic field are related by the celebrated synchronism condition

$$\omega = n\Omega_e + k_z v_z = \frac{neB}{\gamma m_e} + k_z v_z$$

Where $\Omega_e$ is the electron cyclotron frequency, $n$ is the harmonic number, $e$ is the electronic charge, $B$ is the applied magnetic field strength, $m_e$ is the electron rest mass, $\gamma$ is the relativistic factor. $k_z$ is the axial wave number and $v_z$ is the axial speed of the electron beam. In most gyro-devices, Doppler–shift term $k_z v_z$ is quite small, so the operating frequency is equal to an integral multiple of cyclotron frequency.
2.1 Types of Gyro Devices

Among all gyro-devices, the most popular and most explored member is the Gyrotron which finds potential applications in fusion reactors and material processing industries. The next most popular member is Gyro-TWT which is most commonly used for millimeter wave Radar application. Gyro-klystron is also a potential contender of Gyro-TWT. There are other devices, such as Gyro-BWO, Gyro-Twystron, Cyclotron Auto resonance Maser which are still in their initial stage of development [4, 5, 57].

Each of these types offers unique properties and advantages for particular applications. They differ principally in the interaction structure and each has a counterpart in the classical microwave tubes, as implied by the terminology. Russian scientists at IAP Nizhny Novgorod, R.A.S., operated the first gyrotron in September 1964. The name gyrotron was originally used by the Russians for a single-cavity oscillator, now often referred to as a gyro-monotron. The name now refers to a class of devices including both oscillators and amplifiers. Since then, gyrotrons have dominated the millimeter-wave region at a megawatt power level and successfully entered the sub millimeter-wavelength region. As shown in Figure 2.1; there is one-to-one correspondence between linear beam (O-type) tubes and gyro-devices [6]

![Figure 2.1: Linear-beam devices and corresponding gyro-devices Source: [6]](image-url)
2.1.1. Gyro-Monotron (Gyrotron)

Gyrotrons fill an important gap in the spectrum of electromagnetic waves. The components of gyrotron oscillator are shown in Figure 2.2[7, 60-65, 69, 76-78].

![Gyrotron oscillator](Image)

**Figure 2.2**: Gyrotron oscillator Source: [7]

In a gyrotron oscillator, an annular electron beam is generated by the electron beam source normally known as MIG (Magnetron Injection Gun). The external magnetic field produced by a superconducting magnet located at the center of the cavity causes the electrons to gyrate. The gyrating electron beam is transported to the interaction region where, due to beam-wave interaction, a fraction of electron beam power is converted into r.f. power. The magnetic field in the interaction region is tuned in such a way that the cyclotron frequency or one of its harmonics is close to the frequency of r.f. field. In this case, the electron beam interacts with r.f. field and transfers its energy to the r.f. wave. In case of axial output coupling, the spent beam is collected on the uniform output waveguide section. The other type of gyrotron built today is gyrotron with the radial output, where r.f. window is perpendicular to the gyrotron axis for r.f. output.
Typically, a high power gyrotron uses MIG. The electron beam is generated by MIG at the cathode and is accelerated towards the anode to form an electron beam of suitable parameters and passes through the region for interaction with the r.f. wave. For designing an electron gun, the beam parameters such as beam diameter, beam density, beam speeds etc. are taken into account. In MIG, the electron beam generation is based on the principle of thermionic emission. The most common thermionic emitters are tungsten cathode, oxide cathode, dispenser cathode, thorium-based cathode. These days, dispenser type of cathode is usually preferred due to its better emission density, life and reliability. Figure 2.4 [8] shows the schematic view of MIG of a typical gyrotron.

**Electron Beam Generation and Propagation**
The cathode of MIG emits the electron beam which propagates through the interaction structure. At the interaction region, the electron beam transfers its transverse energy to the r.f. wave. This transverse energy is very small in the gun region. Thus a strong magnetic field is required to convert the axial beam speed acquired from the accelerating potential into the transverse speed of the beam.

The magnetic field causes the electron beam to begin to gyrate as the Lorentz force involves the cross product of electric and magnetic fields. Due to rapidly increasing magnetic field, the electron beam is also compressed. Adiabatic theory requires that the electron magnetic moment should be conserved \([8, 69]\). Thus, we can write

\[
v_t = v_{t*} \sqrt{\frac{B_o}{B_{zo}}}
\]

Here, \(v_t\) is the transverse speed of electron, \(v_{t*}\) is the transverse speed of electron in the interaction circuit, \(B_o\) is the magnetic field at cathode. In practice, the adiabatic theory does not give accurate results for the transverse velocity due to space charge effect and rapidly changing electric and magnetic field near the electron gun. For this reason, we are considering a single particle theory neglecting space charge effects. The electron beam is gyrating with the angular frequency given by

\[
\Omega_e = eB_o / m_e \gamma
\]

where \(\gamma\) is the relativistic factor, \(e\) is the electronic charge and \(m_e\) is the rest mass of the
electron. This electron beam interacts with r.f. signal and transfers a part of its energy to r.f. wave. Efficient bunching requires a high quality electron beam. The quality of electron beam is decided by two parameters, the transverse-to-axial velocity ratio of electron beam and the transverse velocity spread. Keeping this aspect into consideration, cathode used in the electron gun is operated in the temperature-limited region rather than in the space-charge limited region to minimize the velocity spread in the electron beam.

**Electron Cyclotron Resonance and r.f. Power Generation**

The interaction between electron beam and r.f. wave takes place in a region known as interaction structure or cavity. The gyrotron interaction cavity is typically a three-section smooth walled open ended cylindrical structure, with tapers of various sizes and lengths on both sides of the middle section. Here, the input section is a down taper section [5], which is a cut-off section; this prevents the back propagation of r.f. power to the gun region. The beam wave interaction takes place mainly in the uniform middle section where the r.f. field reaches peak values. Third section is an up taper section which connects the cavity with the output waveguide. The parabolic smoothing is also done sometimes at the junctions of two sections to minimize mode conversion. This circuit can support an electromagnetic mode depending upon the size of the uniform middle section where the design is made in such way that the desired operating mode is properly excited and then this r.f. mode interacts with the orbital kinetic energy to generate r.f. output. The electrons in the beam, therefore, must have a large transverse speed $v_t$ as well as a longitudinal speed $v_z$. For the gyrotron, most of this transverse velocity comes from the magnetic effect, produced by the increasing magnetic field leading up to the interaction region. The transverse component of the r.f. field in this region interacts with the gyrating annular electron beam and converts large part of the orbital kinetic energy into r.f. power output. The electrons follow a helical path around the lines of force of the external field. In order for the net flow of energy from the transverse electron motion to the electromagnetic wave to take place, the electrons must become bunched in phase within their cyclotron orbits. Such bunching occurs due to the fact that the electron cyclotron frequency is a function of electron energy [8].

As the electron beam moves under the influence of a very high potential, the relativistic effect plays an important role in the beam-wave interaction mechanism. Due to the very high energy
of electron beams (and thus very high electron speed), a kind of frequency shift occurs in the r.f. due to the relativistic Doppler Effect.

In an ECRM (Electron Cyclotron Resonance Maser), electromagnetic energy is radiated by relativistic electrons gyrating in an external longitudinal magnetic field. The cyclotron frequency is proportional to the magnetic field $B_0$ and thus cyclotron frequency does not directly depend on size of resonators or r.f. structure. Because of this aspect, r.f. circuit in a gyro-device is replaced by a simple structure like a smooth waveguide. Their dimensions are not limited and, thus, the power handling ability increases manifold as compared to the conventional slow-wave microwave tubes. The size of the r.f. structure depends on the operating mode. Higher the mode, larger the size of the waveguide and higher is the power handling capability. The helical beam produced by the MIG interacts with the electromagnetic field (in TE$_{mn}$ mode) of the same frequency as the cyclotron frequency when the electron beam passes through the interaction region. This causes bunching of the electron beam.

In order to understand the process by which an annular electron beam amplifies a TE cavity mode, it is convenient to consider a small group of electrons orbiting about the same guiding center.

![Figure 2.5](image)

**Figure 2.5** (a) Annular electron beam with electrons in the random phase (front view), (b) annular electron beam with electrons bunched in phase (front view)
Figure 2.5 (a) and Figure 2.6 (a) show a cross-section of the electron beam and side view of the electron beam at the beginning of the interaction region respectively. Here, in Figure 2.5, $r$ is the electron beam radius, $r_l$ is the larmor radius of electron beam and $E_\theta$ is the azimuthal component of electric field. In the absence of any electric field, the electrons in this beamlet will orbit around the guiding center with an angular frequency given by $\Omega_e$. In the presence of transverse electric field ($E$), the electrons experience an additional force $eE$ which cause some electrons to accelerate and others to decelerate depending on the relative phase of the electric field.

Due to this mechanism, the electrons ultimately form a bunch as shown in Figure 2.5(b) (cross-sectional view) and Figure 2.6(b) (side view). To understand the phase bunching, it is convenient to consider a single orbit case.

Figure 2.6 (a) Annular electron beam with electrons in random phase (side view), (b) Annular electron beam with electrons bunched in phase (side view)

Figure 2.7: Front view of one orbit before electron bunching
In Figure 2.7, electrons 2, 3, and 4 are decelerated, while electrons 6, 7, and 8 are accelerated, and electrons 1 and 5 are undisturbed. Since the cyclotron frequency is inversely proportional to relativistic mass factor, the frequency will decrease for accelerated electrons and increase for decelerated electrons. After few cycles, the electrons that gained energy lag in phase and the electrons that loose energy advance in phase, resulting in phase bunching. If the electric-field frequency is exactly equal to the electron cyclotron frequency, this bunching process will continue until the entire beamlet is bunched at a zero field phase point. In order to extract power, the bunch must be formed at a field maximum. This is accomplished by a slight detuning of the axial magnetic field so that the cyclotron frequency is slightly lower than the r.f. frequency. When this condition is achieved, then the bunches will orbit in phase with the electric field and give up rotational energy to the TE mode of r.f. field[5,9].

**Spent Electron Beam Collection**

The collector assembly of gyrotron acts primarily as a dump for the spent electrons. In the conventional gyrotron, that is, gyrotron with axial r.f. collection (Figure 2.3), the collector also works as a waveguide for r.f. output. The collector is usually insulated from the gyrotron main body. This makes it possible to measure the collector current and body current separately. A reduction in the power density at the collector surface is possible by adding coils around the collector. This either decreases the derivative of the magnetic induction or makes the induction along the length of the collector more uniform. Usually, oxygen-free high conductivity (OFHC) copper is chosen for the gyrotron collector because of its good thermal conductivity.

**Output Power Extraction**

The last gyrotron subassembly is r.f. window which acts as an outlet for the r.f. output power and also functions as a vacuum seal for the tube. It must be fabricated from a low loss material 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 done.
2.1.2. Gyrotron: State of the art

Today a vast number of research institutes and industries are pursuing activities in the field of Gyro-devices worldwide and are achieving newer heights in terms of output power and operating frequency. Some of the state of art development in the field of Gyrotron and Gyro-TWT are presented below:

Large orbit Gyrotron

For a large orbit Gyrotron, guiding center radius of the electron beam is equal to the Larmor radius of the gyrating electron. Hence all the electrons have waveguide axis encircling orbits. Large orbit Gyrotron has got the distinct advantage of the ability to operate at a very high Cyclotron harmonic number ($s \gg 15$) reducing the required background magnetic field by many factors. Large orbit Gyrotron has been reported to deliver peak power of 600 MW at twentieth Cyclotron harmonic.

Multi Frequency Gyrotron

An oscillator generating r.f. power simultaneously at two frequencies (multimode) is usually considered as an undesired phenomenon as this makes the oscillator unstable. But in case of Multi Frequency Gyrotron, this is a desired phenomenon, where the Gyrotron offers stable oscillation and stable r.f. power simultaneously at a number of frequencies (which are not harmonically related). This kind of Gyrotron is very useful for controlling the instability of plasma in thermonuclear reaction. At FZK, Germany, a Gyrotron has been developed which offered multimegawatt power at 9 different frequencies.

Coaxial Gyrotron

In coaxial Gyrotron, a coaxial cavity is used as the interaction structure. This kind of Gyrotron has got many advantages over conventional cavity Gyrotron. Central conductor reduces the voltage depression and corresponding degradation of electronic efficiency. Also, by properly tapering the outer and/or inner conductor radius, the diffractive quality factor of the desired mode can be enhanced. And since the start oscillation current is inversely proportional to the diffractive quality factor, this selective increase in quality factor helps in reducing the chance of oscillation to be set-in in an undesired mode.
2.1.3. Comparison of Gyrotron and Conventional Microwave Tubes

1. In conventional tubes, the r.f. fields with which the electrons must interact are most intense near the circuit surrounding the beam, so the beam must travel as close to the circuit as possible. This leads to beam interception and heating of the circuit.

2. In conventional tubes, circuit heating limits power capability.

3. In conventional tubes, circuit dimensions are on the order of the wavelength of the operating frequency and scale with wavelength so power is severely limited at high frequencies.

4. In conventional tubes, the r.f. circuit must slow down the phase speed of the signal approximately to the beam speed. These tubes are referred to as slow wave tubes.

5. In gyrotrons, the field with which the beam must interact is more intense some distance from the cavity surface. Beam interception problems are far less severe than in linear-beam tubes.

6. The large dimensions and absence of beam interception in gyrotrons make operation possible at extremely high powers and frequencies.

2.1.4. Gyro-Amplifiers

These are Gyro-klystrons, gyro-twystron and gyro-TWT. Gyro-Amplifiers are being developed for applications requiring phase coherence and wide bandwidth. A primary application is radar where they are of considerable interest for future high –performance applications. Gyro-amplifiers have large weight and volume than conventional amplifiers but they can provide significantly higher powers[2].

2.1.5. Gyro-Klystrons

The operation of a Gyro-Klystron, which is again an amplifier, is similar to that of the conventional Klystron except that electron bunching occurs in the azimuthal direction rather than in the axial direction. In Gyro-Klystron, input r.f. signal is fed to the first cavity (catcher cavity) where the cyclotron bunching process is initiated. Then, the beam is permitted to drift. As the beam passes through a second cavity, the amplified signal may be collected or in case of multi cavity Gyro-Klystron, the bunching process may be enhanced and the signal is
collected in a subsequent cavity. A cross sectional view of a two cavity Gyro-Klystron is shown in Figure 2.8. The development of Gyro-Klystron has not been pursued vigorously, apparently, because of the greater promise of Gyro-TWTs [4,10].

![Gyro-Klystron Diagram](image)

**Figure 2.8**: Gyro-klystron Source:[10]

### 2.1.6. Gyro-Twystrons

The gyro-twystron, like the conventional twystron, is a hybrid device with a modest bandwidth capability. It is derived from the gyro-klystron by using the gyro–klystron interaction in the cavities near the r.f. input and by replacing the output cavity with a slightly tapered waveguide section as in the gyro-TWT to be discussed in the subsequent section. The output section is excited by the electron beam, which has been bunched by the interaction in the klystron section.

The configuration of the gyro-twystron can prevent the problem of breakdown at high-power levels because the r.f. power density in the output waveguide can be much smaller than that in the gyro-klystron output cavity [2].
2.1.7. Gyro–TWT

Gyro-TWT is a high power amplifier. In this device, instead of a cavity, a non-resonant interaction structure such as waveguide is used. This device has the potential of amplifying r.f. powers of one order of magnitude larger than what is possible in a conventional TWT and also provides a high spectral quality. In this device, wideband coalescence is achieved by adjusting the background magnetic field for grazing point interception i.e. the group speed of the wave becomes equal to the axial beam speed. Broad-banding of the device is also done by dispersion shaping of the waveguide by various means such as metallic vane loading, metallic disc loading, helical corrugation, dielectric loading of the waveguide etc. Multi section Gyro-TWT is also being developed by incorporating a sever section to suppress backward wave. Techniques are also being used to increase the bandwidth by tapering the waveguide diameter and the magnetic field. This technique however reduces the gain of the device as effective interaction length at a specific frequency becomes smaller [4, 11-16, 56, 66-68, 70, 73-75, 80].

In these devices, a non resonant r.f. structure is used to produce traveling wave interaction. As in other gyro-devices, a spiralling electron beam immersed in an axial magnetic field is used. Traveling waves are launched into the interaction space by an input coupler. Axial phase synchronism is required between the traveling wave and the rotating electrons as indicated in Figure 2.9.

![Figure 2.9: Interaction of beamlet with a traveling wave. Source: Advances in Electronics and Electron Physics, Vol. 55, by R. S. Symons and H. R. Jory, copyright 1981 by Academic Press](image-url)
As the electromagnetic wave and the spiralling electron beam move through the interaction space, the kinetic energy of the electron beam is transferred into the electromagnetic fields, creating r.f. amplification. For typical operation near the cutoff frequency of the interaction waveguide, it is primarily the transverse component of electron motion that interacts with the electromagnetic wave.

An important problem that must be dealt with in gyro-TWT design is maintaining stability and preventing backward wave oscillations (BWO) in the interaction space. At the same time, acceptable performance, including high overall gain, stability to local reflective oscillations, and high average power capability must also be achieved.

To ensure stability, the majority of this interaction space should exhibit a moderate amount of electromagnetic loss per unit length. This distributed loading approach has been shown to have superior stability characteristic compared to the approach using localized lossy severs. Finally, the downstream part of the interaction space is completed with a short, unloaded cylindrical tunnel in which the final, highest powered portion of the amplification takes place [2].