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Title of the Chapter: “High Power Microwave Sources and Applications”

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Abstract:

Gyrotron is a high power microwave source which is used in plasma sciences, material sciences and energy generation. At present the Gyrotron is used almost in every plasma fusion reactors as a high power microwave and millimeter wave source for electron cyclotron resonance heating (ECRH). ECRH frequency of very ambitious plasma fusion reactor named International Thermonuclear Experimental Reactor (ITER). ITER is an international effort (including India) to develop the technology which can convert nuclear energy by plasma fusion process into electricity efficiently. The research in the field of microwave sources including the Gyrotron is a strategic area and thus the international design and development technology is exclusive.

Keywords: Gyro-devices, RF window, Beam wave interaction, Modes, Oscillations

1.1 Introduction

Microwave is serving today the in every house, sphere, starting from kitchen to communication, space sciences to future energy generation. Microwave tubes are basically microwave sources in the microwave frequency band providing high output power. These microwave devices are available with a long list; some popular devices are traveling wave tube (TWT), klystron, crossed-field devices, Gyro-TWT, Gyro-klystron, etc. as amplifiers; while backward wave oscillator (BWO), Gyrotron etc. as oscillators. Vacuum devices are performing vital role leading towards creating quality life style as well as environment for human kind. The scenario of finding newer and newer applications using these devices for better world, today one cannot imagine the world without microwave tubes.

Microwave tube continues to be leader in high power, high frequency regime in spite of challenges continuously coming from solid state devices due to inherent capability of the former in terms of thermal management, reliability, life and cost too if estimated for the same power level, efficiency at the frequency range of application, as well as from EMI and EMC considerations. The applications of microwave tubes cover wide horizons, such as, communication, radar, electronic warfare, directed energy weaponry (DEW) using high power microwaves (HPM), industrial ovens, cooking, material sintering , hyperthermia, plasma heating for controlled thermonuclear energy research, atmospheric sciences, satellite communication and so on [1]-[4]. It is now possible to construct finely grained ceramics of a more uniform microstructure yielding to the development of stronger and less brittle ceramics and new ceramic composite materials with the application of medium and high power millimetre waves generated from the microwave tubes, which gives the advantage of the volumetric and selective heating utilising the property that the absorptivity of a material increases with frequency and therefore, yielding faster and better ceramic sintering [5].

These devices are the potential candidates for providing microwave power in the space-debris removal and phased-array mapping radars as well as for the ground probing radars, the latter for the detection of underground materials, like the gun emplacements, bunkers, mines, geological strata, pipes, voids, etc. Further, these devices are the heart of the impulse radar for the range resolution as well as for the detection of stealth aircraft, etc. and also for the cloud-radar used as a sensor in environmental research, it being believed that clouds can dominate the effect of greenhouse gases in global warming. In addition, it is to be noted that by the middle of the present century, high power microwave tubes in the millimetre-wave frequency range required for plasma heating would greatly contribute to electric power production using controlled thermonuclear fusion bypassing the fission that is associated with the problem of disposing a large quantity of radioactive waste. The first venture to address the technological and scientific tasks of finding alternative source of energy by exploring the fusion power through an ITER program is already in process [6].

Through the development and use of advanced design, materials and technology, the capability of conventional slow-wave microwave tubes, like, the travelling-wave tube (TWT), klystrons, magnetrons, etc. has been enhanced many fold. Moreover, it is interesting to mention here that the realisation of newer devices, such as, microwave power module and micro-fabricated vacuum electronic tubes has added new dimensions to the area of microwave tubes because these devices possess some inherent advantages of the both, solid-state as well as vacuum-electronic devices. Some other unconventional tubes, like, the VIRCATOR, the MILO, the relativistic backward-wave oscillator (BWO), the OROTRON, etc., provide HPM sources, which, for instance, can cater to the need of DEW Also, there are some other unconventional tubes, like, the gyromonotron or gyrotron the gyro-klystron and the gyro- travelling-wave tube (gyro-TWT) [7], based on fast-wave cyclotron resonance maser (CRM) instability as well as the slow-wave cyclotron amplifier (SWCA) based on Weibel instability, and the cyclotron auto-resonance maser (CARM) based on both the CRM and Weibel instabilities, which can provide high powers in the microwave to terahertz frequency range.

Here, it is worthy to mention that the renewed interest in the gyrotron, lies with joining of the world community to create reactor machine through ITER program. High power gyrotrons at different frequencies such 120GHz, 140GHz and 170GHz would be required for ITER machine in this program.

1.2 History of Microwave Tubes

Microwave tubes (e.g., helix TWTs) provide very wide bandwidths ~ 2-3 octaves required in electronic warfare (EW) (like, electronic counter measure (ECM) and electronic counter counter measure (ECCM)) systems. Microwave tubes meet the requirement of the communication sector by way of providing moderate CW power, relatively narrower bandwidth as compared to the requirement of the EW sector, high gain, low group delay, low AM-to-PM conversion coefficient, good reliability, long life, high efficiency (for instance, for space applications), etc. For applications, such as, plasma heating and electron acceleration, the demand is for very high CW power ~ 250kW to 1MW as well as for very high pulsed power upto ~ multi megawatts. Microwave tubes are also in demand for industrial heating in various industries, like tea, paper, wood, leather, food grains, etc. Microwave tubes find applications in the medical sector as well, for instance, as applicators in hyperthermia for the treatment of cancer. Microwave tubes are based on the mechanism of conversion of EM radiation from individual electrons into coherent radiation by bunching the electrons in proper phase with respect to the RF wave by adjusting the electron beam. Accordingly, microwave tubes are classified in different possible ways, such as (i) O-type and M-type; (ii) slow-wave and fast-wave types; (iii) longitudinal space-charge wave, transverse space-charge wave, and cyclotron mode interaction types; (iv) kinetic and potential energy conversion types; and (v) Cerenkov, transition, and bremsstrahlung radiation types [9].

In an O-type microwave tube, a DC axial magnetic field constrains the electrons to move in the interaction structure as a linear beam. The device is hence also called a linear beam tube. In such a type of tube, the magnetic field does not take part in the beam-wave interaction process; the longitudinal space-charge wave interaction takes place; the axial kinetic energy of the electron beam is converted into electromagnetic waves; and a slow wave mode is destabilised. On the other hand, in an M-type tube, a DC magnetic field, applied perpendicular to the electric field, takes active role in the beam wave interaction process. In this type, the transverse space-charge wave interaction takes place and the potential energy of the electron beam is converted into electromagnetic waves. while those like magnetron and CFA belong to the M-type. In the devices, like, gyrotron, a fast cyclotron wave interacts with a fast waveguide mode, and the magnetic field takes a dominant role in the cyclotron resonance instability mechanism of the device. The TWT may also be classified as a Cerenkov radiation type of microwave tube in which the electron beam velocity is synchronised with the phase velocity of electromagnetic waves in the interaction medium. Similarly, one may have a class of microwave tubes belonging to bremsstrahlung radiation type, in which the electrons bremsstrahlung, that is, move with an acceleration or deceleration in an electric field, as in a virtual cathode oscillator (VIRCATOR), or in a magnetic field, as in a gyrotron.

The magnetrons, which belong to the M-type, are most extensively used as oscillators in early radars, usually as pulsed power sources, and are available from 0.5GHz to 50GHz operating frequencies with reported power upto 5GW. In the simplest configuration, the magnetron has a cylindrical cathode surrounded by a cylindrical thick anode with resonator slots, which open towards the cathode. In other configurations, they are available as the coaxial, inverted, and rising-sun magnetrons. A typical millimetre-wave rising-sun magnetron has reportedly delivered 100kW at 48GHz. The CFA is another useful M-type tube. The tube is highly efficient though at a low gain value, and enjoys the attractive features, such as low operating voltage, small size, light weight, and moderate bandwidth making them suitable for transportable and airborne applications. The S-band CFAs have been developed giving typically 1MW peak and 20kW average powers, with efficiency as high as 80% with a nominal gain of 30dB. The CFAs are often preferred to the TWTs in certain applications, such as, in the final amplifier stage of a radar transmitter. It is however felt that, as the operating frequency is increased to the millimetre wave range, the beam interception as well as RF losses at the anode-cum-slow-wave structure makes a CFA less competitive, with respect to the average power capability than an O-type tube, such as, klystron or TWT.

The klystrons belonging to the family of the O-type tubes find wide applications in communication systems and accelerators, have been built at frequencies from 0.5 to 35GHz, yielding CW power over 1MW and pulsed power over 100MW with gain values ranging from 10dB to 70dB. The multi-megawatt, multi-beam klystrons have also been built yielding several tens of kilowatts or megawatts of power at several hundreds of megahertz frequency, for the linear accelerators and synchrotrons for the study of high-energy physics.

The TWT is similar to the klystron in that it belongs to the family of O-type in one of the different ways of classifying microwave tubes already discussed. However, in another way of classifying microwave tubes, the TWT belongs to the Cerenkov radiation type of tubes, unlike the klystron that belongs to the transition radiation type. The power capabilities of TWTs range from few watts to the ~ megawatts, and they are available at lower microwave frequencies as well as at millimetre waves. The two types of TWTs are most extensively used in numerous applications. They are, the coupled-cavity and the helix TWTs, the former using a coupled cavity and the latter a helix as the slow-wave interaction structure. Unlike a helix TWT, which uses a non-resonant helix interaction structure that has a wideband potential, a coupled-cavity TWT has a limited bandwidth, as it uses, a stack of resonant cavities with suitable coupling between adjacent cavities, as the interaction structure. Coupled-cavity TWTs, however, have a higher power capability than a helix TWT, and they are used in surface and airborne radars, as well as in high power, millimetre-wave communication systems.

This limits the power capability of these tubes at high frequencies, specially, in the millimetre-wave frequency range. In sixties, gyrotrons used for heating fusion plasma, which are based on the principle of cyclotron resonance maser instability (CRM), came into being. The sizes of these devices do not shrink as much as do those of the conventional slow wave microwave tubes. Subsequently, other gyro-devices (CRM instability based devices), like, gyro-klystron and gyro-TWT, etc. were also developed. Thus, with the advent of gyro-devices, there has been a quantum jump in the high frequency and high power capability of the microwave tubes. Gyrotron is basically a fast wave device, which uses a smooth wall circular waveguide (large resonator) in which no attempt is made to reduce the velocity of the wave, so here the phase velocity, v_p, is more than the velocity of light, c. Here, the electron beam is injected into the electromagnetic field in a manner such that sustained beam wave interaction takes place.There is intense interest in these fast wave devices at present time. It stems from the simplicity of the RF structure and the fact that the electron beam is normally placed well away from the RF structure. The result is that the size limitation is significantly relaxed. With larger dimension, the power handling capacity is also significantly increased.

1.3 Electron beam generation and propagation

The electron beam is generated by an electron gun at the cathode and accelerated towards the anode in any microwave tube. Electron gun is the heart of any electron beam device and used to provide electron beam suitable for the beam wave interaction. In Gyrotron oscillator an annular electron beam is produced by the electron gun also known as magnetron injection gun (MIG). The electron gun is used to generate an electron beam with the beam properties (beam diameter, beam density etc.) required at interaction structure for its interaction with the RF wave. The high power gyrotron typically uses the thermionic magnetron injection gun (MIG) which produces large annular electron beams with the electron beams with the electrons executing small cyclotron orbits as required for the cyclotron resonance interaction. Fig. 1.1 shows the schematic view of a triode type magnetron injection gun with electron beam profile. Another type of MIG is diode-type MIG, where only one anode is used. In MIG, the electron beam is emitted from the conical shaped cathode working 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 external magnetic field produced by a superconducting magnet located at the center of the cavity causes the electrons to gyrate. This gyrating electron beam is propagated towards the interaction region through beam tunnel. This electron beam interacts with RF signal and transfers a part of its energy to RF. The spent beam leaves the cavity and spreads due to decreasing axial magnetic field. After some distance it is collected by the collector. Efficient bunching requires a high quality electron beam. The quality of electron beam is mainly decided by two parameters, namely, velocity ratio (α) and velocity spread, respectively. The velocity spread must be small in both the axial and the transverse directions. Keeping this aspect into consideration, the emitter used in the electron gun is operated under temperature limited region rather than the space charge limited region to minimize the velocity spread in the electron beam.

Fig.1.2 shows the schematic view of Gyrotron under indigenous development at CEERI. The beam tunnel provides the path for the gyrating electron beam from the magnetron injection gun (MIG) to the interaction cavity. The magnetic field is strongly inhomogeneous in the beam tunnel so that the gyrating electron beams are compressed sufficiently to achieve the required beam parameters for the interaction in the cavity. Approximately 3% to 5% of generated RF power in cavity can reach the MIG. This amount of RF power is sufficient to degrade the beam quality and even can damage the MIG cathode. The beam tunnel is mainly used to prevent the propagation of generated RF power from the cavity to the MIG. Lossy ceramics are used in the beam tunnel to absorb the RF power and to avoid the excitation of the parasitic modes. An absorbing beam tunnel of alternate rings of oxygen free high conductive (OFHC) copper and lossy dielectric material is widely used in the Gyrotron. The grounded conductor rings are placed between lossy ceramic rings to remove the charge accumulated on the surface of the lossy ceramic rings during the absorption of RF power.

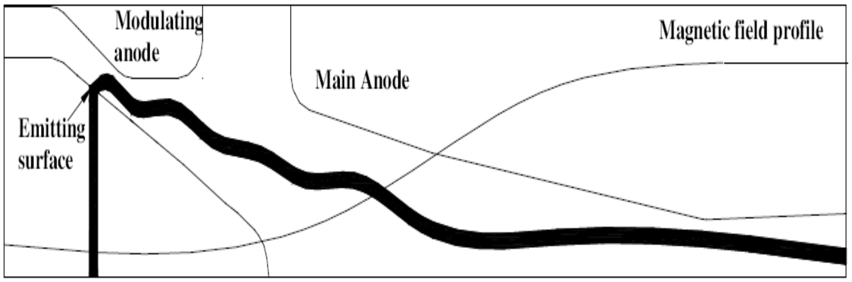

Fig 1.1: Schematic view of magnetron injection gun with electron beam profile

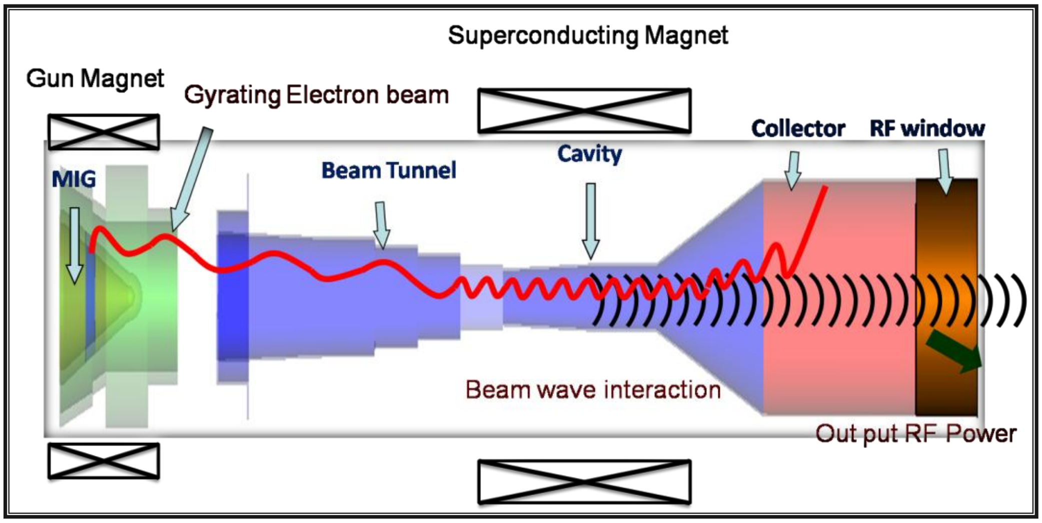

Fig.1.2: Schematic diagram of a conventional Gyrotron

After crossing the beam tunnel, this gyrating electron beam is transported to the interaction region (also called cavity) where due to beam-wave interaction; a fraction of electron beam power is converted into RF power. In conventional gyrotron, the cavity is usually a three-section smooth walled cylindrical structure as shown in Fig. 1.3. The input taper is a cut-off section, which prevents the back propagation of RF power to the electron gun. The beam wave interaction takes place mainly in the uniform middle section where the RF field reaches peak values. The up taper connects the cavity with the output wave-guide. This circuit can support many different electromagnetic modes. The RF fields in this region interact with the orbital kinetic energy into RF output.

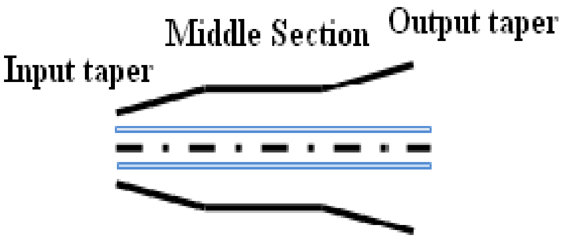

Fig.1.3: Interaction structure with gradually tapered cylindrical wave-guide

The magnetic field causes the electron beam to begin to gyrate as the Lorentz force contains the cross product of electric and magnetic fields. Due to rapidly increasing magnetic field, the electron beam is also compressed. The electron beam starts gyrating with the electron cyclotron frequency (Ω_c) given as [1]-[2]:

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

where *Bo* is the magnetic field at the cavity, *e* is the electronic charge, m_o is the rest mass of electron, and γ_o is the relativistic mass factor, respectively. The beam wave interaction produces angular velocity modulation, which in turn produces a modulation of electron energy. This can produce 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 [1]-[2]:

$$\omega - k_z v_z = \mathrm{s}\Omega_\mathrm{c} \tag{1.2}$$

Here, ω is the wave angular frequency, k_z is the characteristic axial wave number, v_z is the translation electron drift velocity and *s* is the harmonic number, respectively. In case of gyrotron, v_z is always kept below $v_\perp$ (transverse velocity of electrons) and thus the Doppler shift term becomes very small and thus (1.2) becomes:

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

The helical beam produced by the magnetron injection gun interacts with the electromagnetic field (in $\mathrm{TE}_{m,n}$ mode) of the same frequency as of the cyclotron frequency, when the electron beam passes through the 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 [1]-[2]:

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

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

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

where $\chi'_{m,n}$ is the m^{th} root of corresponding Bessel function ($\mathrm{TM}_{m,n}$) or derivative ($\mathrm{TE}_{m,n}$) and r_o is the waveguide radius, respectively. Phase velocity synchronism of the two waves is desired in the intersection region.

The important subassembly of the gyrotron is the RF interaction structure, also known as resonator cavity, which is usually a three-section smooth walled open ended cylindrical cavity structure. Here, the input section is a down taper section, which is a cut-off section, this prevents the back propagation of RF power to the gun region. The beam wave interaction takes place mainly in the uniform middle section where the RF field reaches peak values. Third section is a up taper section, which connects the cavity with the output waveguide. The parabolic smoothing is also done at the junction of two sections to minimize the mode conversion. This circuit can support 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 excited properly, and then this RF mode interacts with the orbital kinetic energy to generate RF output. The electrons in the beam, therefore, must have a strong transverse velocity $v_\perp$ as well as the longitudinal beam velocity 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 ratio of the transverse to the longitudinal velocity, $\alpha = v_\perp / v_z$ in the interaction region is typically selected between 1 and 2, for the gyrotron. For the relativistic beam gyrotron with thermionic emission cathodes, this ratio is usually not less than unity. In this device relativistic operation has brought increased power through the use of stronger beam fields coupling within the interaction region.

The collector assembly of gyrotron acts primarily as a dump for the spent electrons. In the conventional gyrotron, it also functions as a waveguide for RF 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. Until now, gyrotron at 120GHz have interaction efficiency of less than 35% in long pulse operation. A large fraction of the energy (60%-70 %) remains in the electron beam. The addition of an energy recovery system can significantly increase the overall efficiencies. The separation between beam and RF wave in high power gyrotron allows the installation of a depressed collector for the recovery of the residual electron energy. The depressed collector scheme consists of one or more electrodes.

The last gyrotron subassembly is RF window, which acts as an outlet for the RF output power, it is also used as a vacuum seal for the tube. It must be fabricated from a low-loss 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 disc window. For high power gyrotron a temperature of 77˚K or lower is necessary to minimize the reflections.

Besides, the gyrotron subassemblies discussed above, some additional subassemblies, like, beam tunnel, output taper and focusing system are also used. The beam tunnel is a component placed between the electron gun and the interaction cavity. It serves as a region where the electron beam gets stabilized. Most importantly, the beam tunnel region also serves as the absorber for the back propagating RF wave, if any. This is to protect the gyrotron electron gun heating due to reflected RF power from the interaction structure. However, there is chance of parasite oscillations in the beam tunnel itself. The design of the beam tunnel should be such that it should have some lossy material to absorb RF power and no continuous waveguide section to avoid the parasite oscillations.

An output taper is also placed between interaction structure and collector of the gyrotron. In a conventional gyrotron, having axial collection of RF wave, the output taper is a non-linear tapered waveguide, i.e., a continuously varying special radial contour designed to provide the mode purity in transfer of RF mode from the interaction structure to the window as well as no RF interaction in the non-linear tapered section itself as both RF and electron beam are passing along the same path. In the quasi optical gyrotron, it basically consists of a number of parabolic mirrors, so that RF is collected through gyrotron window at right angle to the beam propagation. Lastly, an important subassembly in the gyrotron is the focusing system, it provides the right magnetic field on the electron beam, so that electron beam gyrates properly and is effective for interaction with RF wave. The focusing is a superconducting magnetic system and placed around the interaction cavity.

Gyrotron is based upon cyclotron resonance phenomenon recognized around fifty years back and activities were started in different countries to understand the theoretical concepts, where RF generation takes place due to interaction between the electron beam and fast wave, and also practical demonstration of this phenomenon at low frequency and low power. Since then, the progress in gyrotron is tremendous with almost reaching 1-2MW power at 140GHz and 170GHz.

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