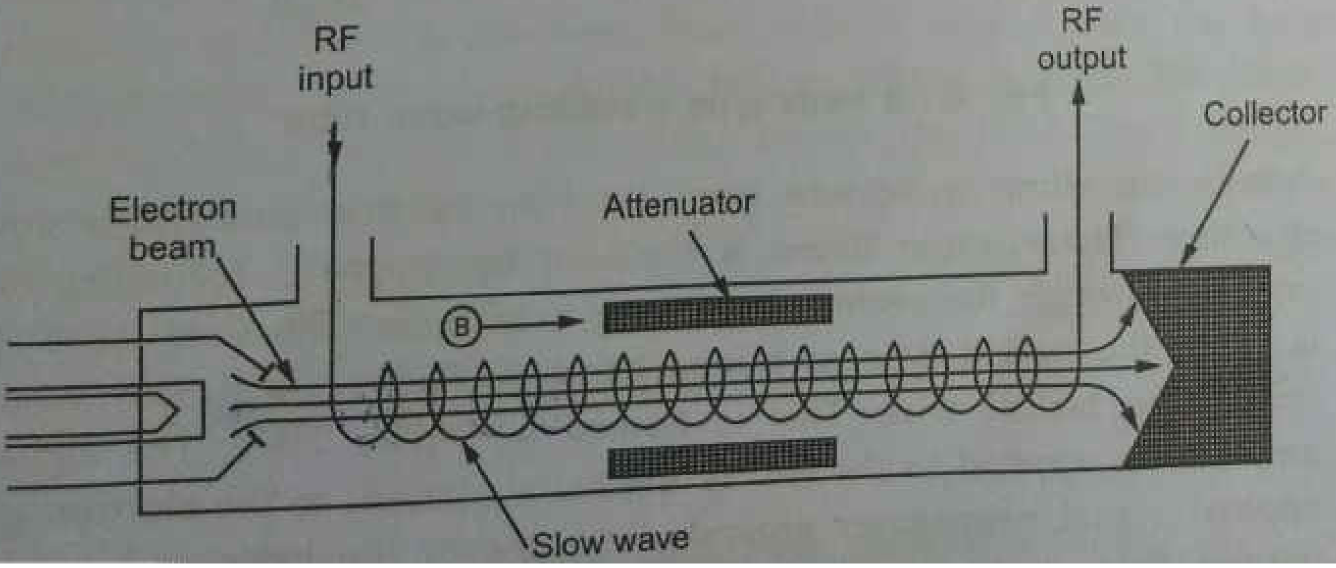
Unit-VI

Helix TWTs

.1 Travelling Wave Tube (TWT)

- The travelling wave tube is an amplifier which makes use of a distributed interaction between an electron beam and a travelling wave.
- The travelling-wave tube (TWT) is an O-type, parallel-field, linear beam device, but it differs from the Klystron in that the RF field and the electron beam interact with each other over the entire length of the active region, instead of only at the cavity gaps. Although TWTs exist that use resonant cavities, most TWTs are nonresonant devices and hence have wider bandwidths than Klystrons.
- Fig. 6.1.1 shows the basic structure of the travelling-wave tube. The electron gun is the same as in the Klystron, but the RF interaction region differs considerably ; its principal feature is a slow wave structure. The goal in this design is to slow down the RF wave, which propagates at the speed of



light (c), to a phase velocity close to the velocity of the electron beam. Under this condition, direct interaction occurs between the RF wave and the electron beam. Synchronized velocities allow both velocity and density modulation of the electron beam.

- The RF wave propagates at the speed of light ($c = 3\times10^8$ m/s), while electron beams propagate at much slower velocities. For example, in a 1500-V electric field, electron velocity is about c/13. To synchronize with such a beam, an RF wave must be slowed down to one-thirteenth of the normal velocity. The mechanism that reduces RF wave phase velocity in a TWT is the slow wave structure, also called a periodic delay line.

Slow Wave Structure

- Several different forms of slow wave structure are commonly used in TWTs single helix, folded or double helix, ring bar and coupled resonant cavity.
- The helix form of slow wave structure uses a conductor wound into a helical space. In most devices the slow wave helix is wound from flat tungsten or molybdenum, but in a few devices hollow tubing is used. The latter design uses the hollow section of the tubing for cooling fluid. The pitch (P) of the helix is scaled to reduce the RF wave phase velocity to the electron beam velocity. The phase velocity (V_P) of an RF signal traveling along a slow wave helix is given by

$$V_P = \frac{cP}{\sqrt{P^2 + (\pi d)^2}}$$

where, V_P = phase velocity in meters per second (m/s)

c = 3×10^8 meters per second (m/s)

P = helix pitch in meters

d = helix diameter in meters

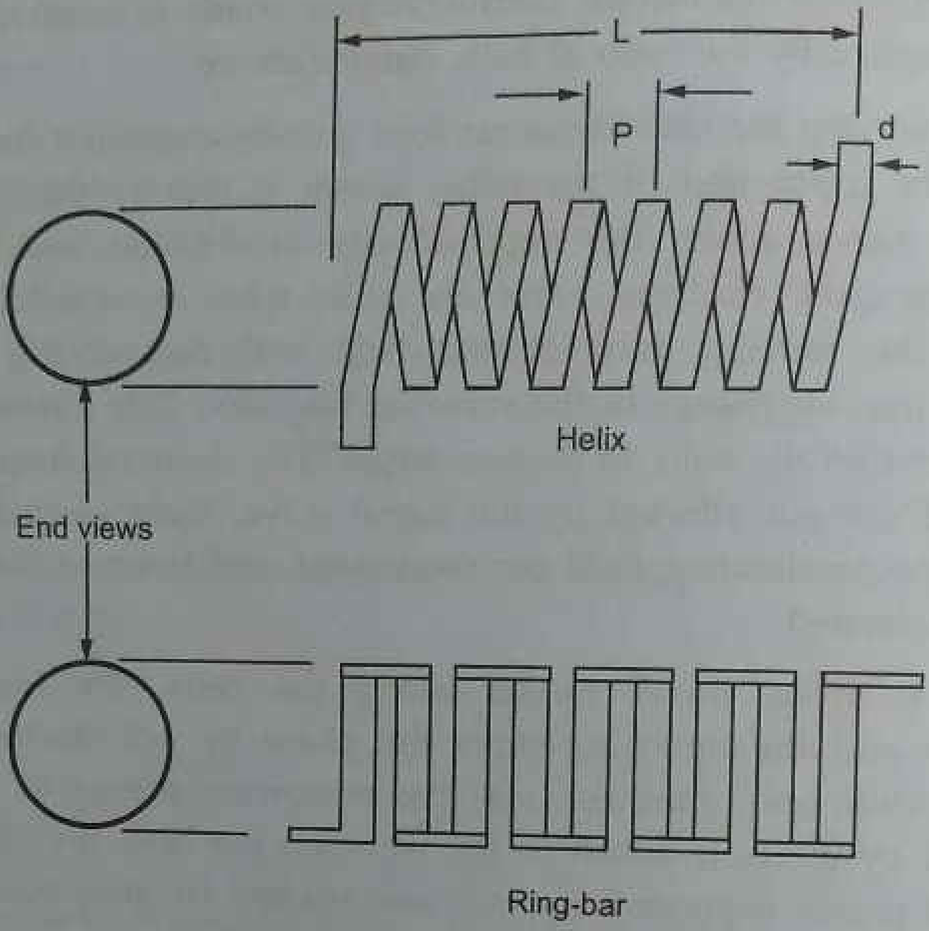


Fig. 6.1.3 Slow wave structures

Need of Slow Wave Structure

1) Slow wave structures are used to reduce the wave velocity in a certai direction so that the signal and the electron beam can interact.
2) For producing larger gain over a wide bandwidth.

Oscillations in TWTs

The slow wave structure is bidirectional, so signals can propagate in both directions. When a signal is reflected from the output coupler, it propagates backward along the slow wave structure to become a feedback signal capable of causing oscillations. Some pulsed TWTs exhibit this problem by brief oscillation bursts at turn on or turn off, but do not oscillate during the on time. This type of oscillation is called 'rabbit ears' because of its appearance on an oscilloscope display of the pulse. Oscillation due to reflected backwave phenomena can be reduced by inserting an attenuator into the middle third region of the slow wave structure. Another alternative, which is less lossy to the forward wave signal, is the use of internal impedance terminations called severs. In most cases, one sever is used for each 15 to 20 dB of TWT gain.

6.1.5 Applications in TWTs

6.1.5.1 Gain in TWTs

- The gain of a travelling-wave tube is proportional to the length of the slow wave structure and is found from

$$\text{Gain (dB)} = \left[\frac{47.3\,FL}{2\pi V_0}\sqrt[3]{\frac{IK}{4V}}\right] - 9.54$$

where

Gain (dB) = gain in decibels

F = RF frequency in hertz

V_0 = electron velocity, $0.593 \times 10^6 (V)^{1/2}$

K = helix impedance in ohms

V = applied dc voltage

I = dc current

The 9.54 factor is to account for losses in the TWT input section.

6.1.5.2 Gain and Power Characteristics

- RF output power does not increase proportionately with increase in RF input power. It starts diminishing after achieving maximum output or saturation point as gain also diminishes. Fig. 6.1.4 shows output power and gain characteristics.

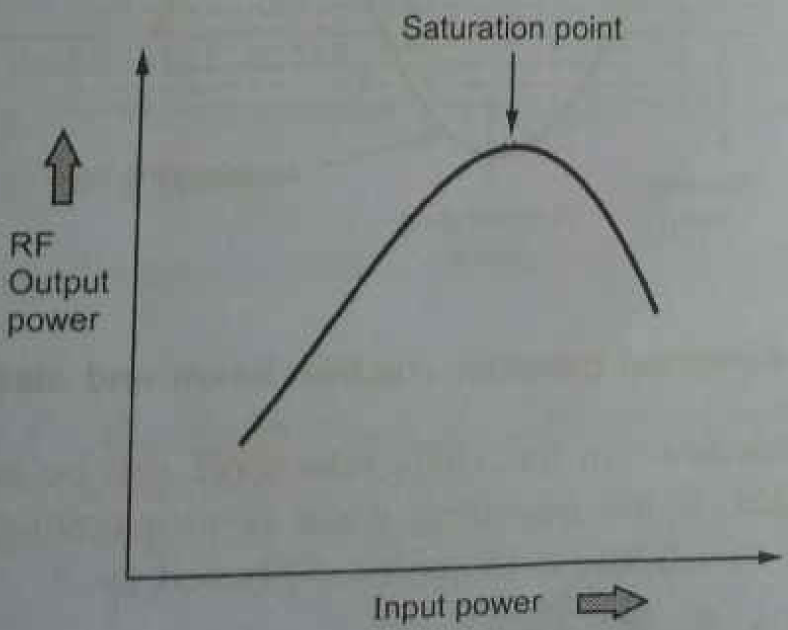


Fig. 6.1.4 Power characteristics

6.1.3.4 Wave Modes / Propagation Constants

- From equation (12) and (19), it is clear that there are four distinct solution for propagation constant. This means there are four mode of travelling wave in TWT. By substituting equation (12) and (19), we get

$$(\gamma^2 - \gamma_0)^2 (j\,\beta - \gamma)^2 = \frac{-j\gamma^2 \gamma_0 Z_0 \beta}{2V_0} \qquad \ldots(20)$$

- The equation (20) is of fourth order in γ and it has four roots. The exact solutions can be obtained with numerical methods. However the approximate solutions may be found by equating the dc electron beam velocity to the axial phase velocity of the travelling wave,

$$\gamma_0 = j\beta$$

then equation (20) reduces to :

$$(\gamma - j\beta)^3 (\gamma + j\beta) = 2C^3 \beta^2 \gamma^2 \qquad \ldots(21)$$

where C is **travelling wave tube gain parameter** and is defined as

$$\boxed{C = \left(\frac{I_0 Z_0}{4V_0}\right)^{1/3}}$$

- from equation (21), it is clear from the term $(\gamma - j\beta)^3$ that there are three forward waves travelled in TWT. From term $(\gamma + j\beta)$ it is clear that there is one backward wave travels in opposite direction to electron beam in the TWT.

Let the propagation constant of three forward waves be

$$\gamma = j\beta + \beta C\,\delta \qquad \ldots(22)$$

(where $C\,\delta << 1$)

Substitution of equation (22) in (21) fields

$(\beta C\delta)^3\ (j2\beta - \beta C\delta) = 2C^3\ \beta^2\ (-\beta^2 - 2\ j\beta\ C\delta + \beta^2\ C^2\ \delta^2)$

Since $C\delta << 1$, the above equation reduced to

$$\delta = (-j)^{1/3}$$

Equation (23) can be written in exponential form as

$$\delta = (-j)^{1/3} = e^{j}\left[\left(\frac{\pi}{2} + 2n\pi\right)/3\right]$$

from n = 0, 1, 2, 3

the first roots δ_1 at n = 0 is

$$\delta_1 = e^{-j\pi/6} = \sqrt{\frac{3}{2}} - j\frac{1}{2}$$

$$(\because e^{-i\theta} = \cos\theta - i\sin\theta)$$

for n = 1, $\delta_2 = e^{-j\pi/6} = -\sqrt{\frac{3}{2}} - j\frac{1}{2}$

for n = 2, $\delta_3 = e^{-j3\pi/2} = j$

The fourth root δ_4 (backward wave can be obtained by equation)

$$\gamma = -j\beta - \beta C\delta_4$$

Similarly, $\delta_4 = -\dfrac{jC^2}{4}$

The values of four **propagation constants** or Gain are given by

$$\boxed{\begin{aligned} \gamma_1 &= -\beta\frac{C\sqrt{3}}{2} + j\beta\left(1 + \frac{C}{2}\right) \\ \gamma_2 &= \beta\frac{C\sqrt{3}}{2} + j\beta\left(1 + \frac{C}{2}\right) \\ \gamma_3 &= j\,\beta\,(1 - C) \\ \gamma_4 &= -j\,\beta\left(1 - \frac{C^3}{4}\right) \end{aligned}}$$

Nature of Four Propagation Constants

These four propagation constant represents the four different modes of wave propagation in TWT. It is concluded that

- In wave corresponding to γ_1, the amplitude grows exponentially with distance.
- In wave corresponding to γ_2, the amplitude decays exponentially with distance.
- In wave corresponding to γ_3, the amplitude remains constant.
- In wave corresponding to γ_4, the amplitude of wave remains constant but direction is opposite.

Performance Characteristics of TWT

1. Efficiency = 20%
2. Power output = 10 kW (average)
3. Power gain = 60 dB
4. Operating frequency > 3 GHz
5. Bandwidth = 0.8 GHz
6. Noise figure = 4 to 8 dB.

Applications of TWT

1. Low noise tubes are used in RF amplifiers in broadband microwave receivers.
2. Repeater amplifier in wideband communication links.
3. Medium and high power satellite transponder output.
4. CW radar and radar jamming.
5. Pulsed high power tubes are used in airborne and shipborne radar.

Comparison of TWT and Klystron

	TWT	Klystron
1.	Field travels along with beam.	Field is stationary and only beam travels.
2.	The interaction of electron beam and RF field in the TWT is continuous over the entire length of the circuit.	Interaction of electron in the Klystron occurs only at the gaps of a few resonant cavities.
3.	The microwave circuit is non resonant.	Klystron circuit is resonant type.
4.	The wave in TWT is a propagating wave.	In Klystron wave is not propagating.
5.	TWT uses non-resonant wave circuits for input and output.	Klystron uses cavities for input and output circuits.
6.	Wide band device because use of non-resonant wave circuit.	Narrow band device due to use of resonant cavities.

7.	In coupled cavity TWT there is a coupling effect between the cavities.	In Klystron each cavity operates independently.
8.	High power output	Low power output
9.	Long life	Short life

5.1.10 important Expressions of TWT

Let Beam current = I_0

Characteristic impedance of Helix = Z_0

Beam voltage = V_0

Gain parameter = C

Output power gain = A_p

Circuit length = N

Frequency = f

Phase constant = β

Length of slow wave structure = l

Gain constants = $\gamma_1, \gamma_2, \gamma_3, \gamma_4$

Then,

i) Phase constant

$$\beta = \frac{\omega}{V_0}$$

ii) Output power gain

$$A_{p(dB)} = -9.54 + 47.3\,NC$$

iii) Gain constants :

$$\gamma_1 = -\beta C \frac{\sqrt{3}}{2} + j\,\beta_e\left(1+\frac{C}{2}\right)$$

$$\gamma_2 = \beta C \frac{\sqrt{3}}{2} + j\,\beta_e\left(1+\frac{C}{2}\right)$$

$$\gamma_3 = j\,\beta\,(1-C)$$

$$\gamma_4 = -\,j\,\beta\left(1-\frac{C^3}{4}\right)$$

iv) Gain parameter $C = \left(\frac{I_0 Z_0}{4 V_0}\right)^{1/3}$

v) Interaction region (circuit length) N

$$N = \frac{l}{\lambda_e} = \frac{l\omega}{2\pi f_0}$$

vi) Frequency $f = 0.593\times10^{6}$

6.2 M-type Tubes

- Magnetrons are M-type devices or crossed field tubes in which the dc magnetic field and dc electric field are perpendicular to each other. In these tubes the dc magnetic field plays a direct role in RF interaction.

6.2.1 Principle of Operation

- The crossed field magnetron is a microwave generator device that uses electrical and magnetic fields crossed at right angles to each other in an interaction space between cathode and anode. The basis for operation of the device is the magnetron principle shown in Fig. 6.2.1.

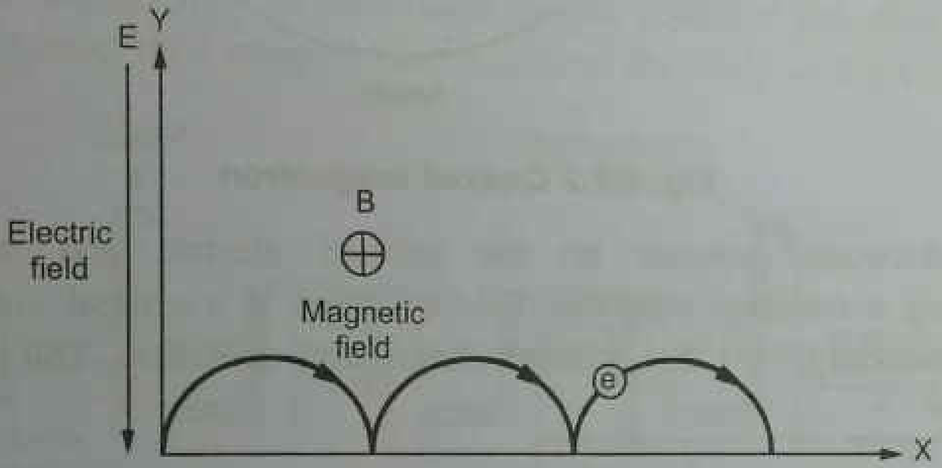


Fig. 6.2.1

- Magnetron principle is derived from path of electron in crossed magnetic and electrical field.
- When an electron is injected into an electrical field it will accelerate from the cathode to the anode in a straight line. But if a perpendicular magnetic field is also present, then the electron moves in a curved cycloidal path. By properly arranging the cathode and anode structure, it is possible to keep the electron cloud of the space charge moving in a curved path. This case is called the **planer magnetron**.
- Fig. 6.2.2 shows a simplified coaxial magnetron consisting of a circular cathode inside a circular anode. The electrical field is such that the negative side is connected to the cathode and the positive side is connected to the anode. A magnetic field from an external permanent magnet has its lines of force perpendicular to the electrical field, as indicated by the arrow (B) into the page of Fig. 6.2.2.
- As it was true in conventional gridded vacuum tubes, the cathode produces an electron space charge by thermionic emission. The ultimate history of

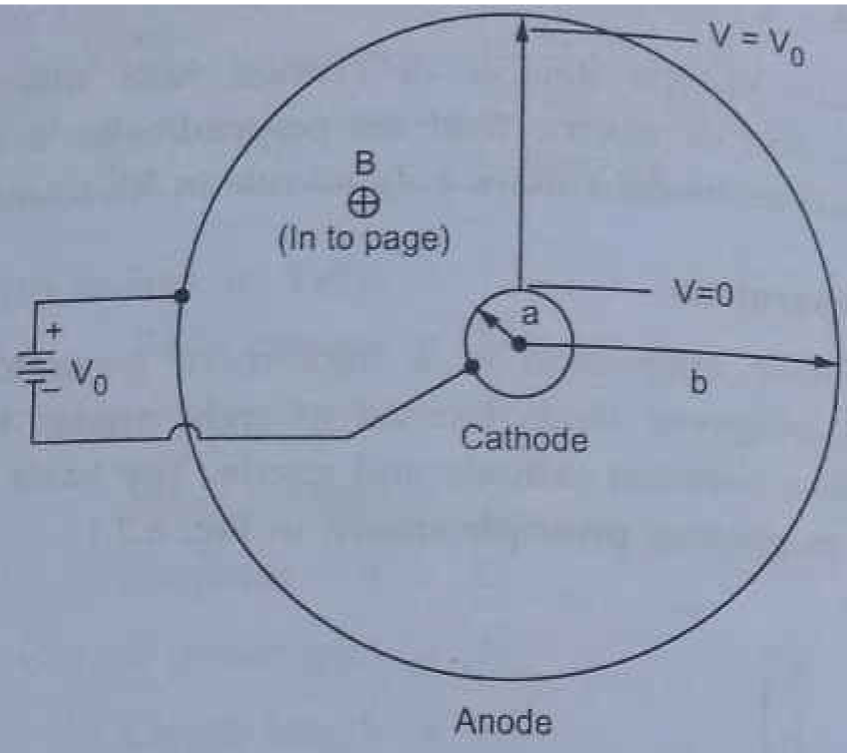


Fig. 6.2.2 Coaxial magnetron

those electrons depends on the applied electric and magnetic fields. Assuming a constant magnetic field(B), there is a critical voltage called the **Hull potential** (V_{0C}) that governs magnetron operation. The hull potential is given by

$$\boxed{V_{0C} = \frac{e\,b^2\,B^2}{8\,m}\left[1-\frac{a^2}{b^2}\right]^2}$$

where

V_{0C} = Hull potential in volts

a = cathode radius in meters

b = anode radius in meters

e = electronic charge (1.6×10^{-19}) coulombs

m = mass of an electron $(9.11 \times 10^{-31}$ kilograms)

B = magnetic field density in webers per square meter (Wb/m^2)

Magnetrons

Magnetrons provide microwave oscillation of very high peak power. The magnetron was invented by Hull in 1921 and in 1939 improved high power magnetron was developed by Randall and Boot.

The magnetron is a self contained microwave oscillator that operates differently from linear wave tubes, such as the TWT and Klystron. The magnetrons are cross field tubes in which electric and magnetic fields are perpendicular to each other, so these tubes are known as M-type microwave tubes. Fig. 6.2.6 shows a travelling wave cylindrical magnetron tube schematic.

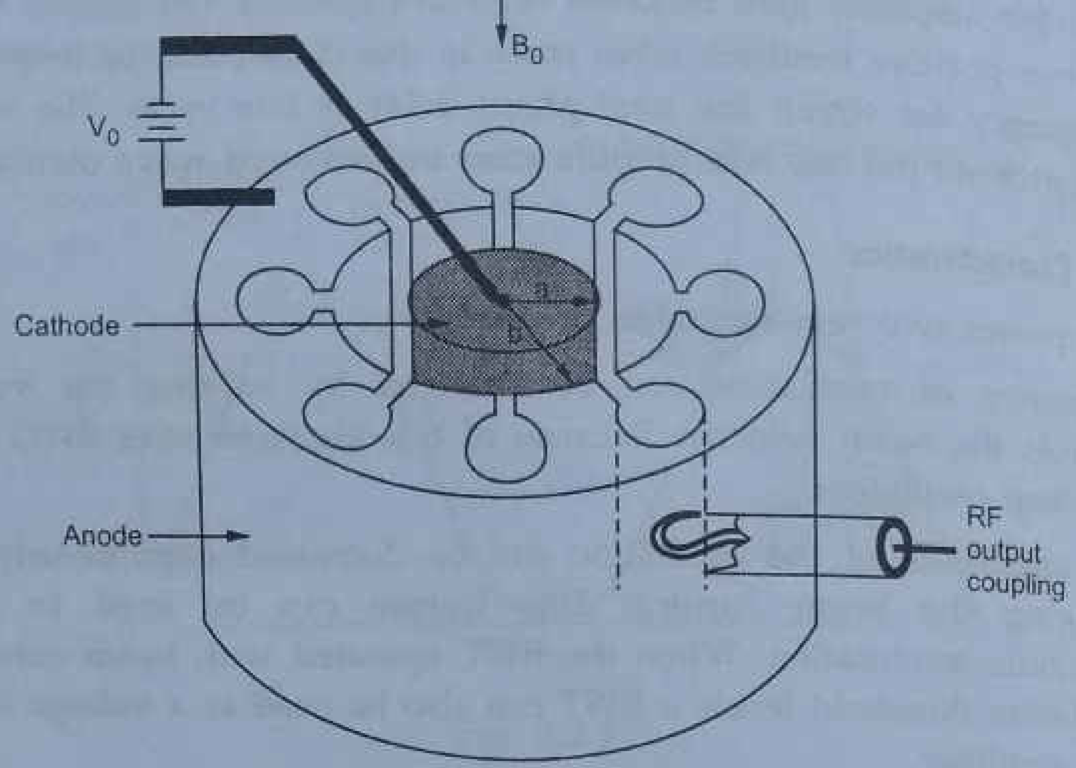


Fig. 6.2.6 Cylindrical magnetron

6.2.3.1 Construction of Magnetron

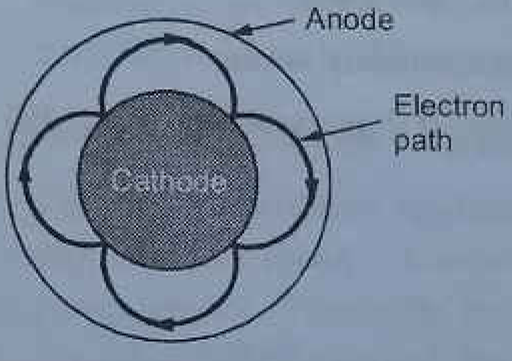
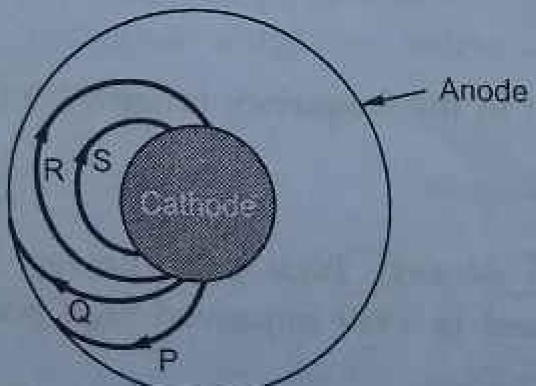


Fig. 6.2.7 Electron path under balanced condition



Electron path	Magnetic field strength
P	Zero
Q	Small
R	Critical (cut-off)
S	Greater

Fig. 6.2.8 Electron path for various magnetic field strength

- Cylindrical magnetron consists of a cylindrical cathode of finite length and radius 'a' at the centre surrounded by a cylindrical anode of radius 'b'. The anode has several re-entrant cavities which are equi-spaced around the circumference. These cavities are connected between anode and cathode by slots. The dc voltage V_0 is applied between anode and cathode. The magnetic flux density B_0 is maintained in positive-z direction by an electromagnet. If the dc voltage (V_0) and the magnetic flux (B_0) are adjusted properly then under the combined forces the electrons follow the cycloidal path between anode-cathode space. Fig. 6.2.7 shows the cycloidal path of electrons under the balanced electric and magnetic field strength.
- The path of electron for various magnetic field strength are shown in Fig. 6.2.8.
- The open space beween cathode and anode is called the **interaction space**. In this space, the electric and magnetic fields interact to

exert force upon the electrons. The magnetic field is usually provided by a strong permanent magnet mounted around the magnetron so that magnetic field is parallel with the axis of the cathode.

Equation of Electron Motion / Trajectory

- The force exerted on electron under the influence of magnetic field of flux density B_z is proportional to charge on electron (e) and flux density B_z. Assuming B_0 and B_z are in positive z-direction.

In rectangular co-ordinates the motion equation of electron is given as

$$\frac{d^2r}{dt} - r\left(\frac{d\phi}{dt}\right)^2 = \frac{e}{m}E_r - \frac{e}{m}rB_z\frac{d\phi}{dt}$$

$$\boxed{\frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\phi}{dt}\right) = \frac{e}{m}B_z\frac{dr}{dt}}$$

6.2.3.2 Types of Magnetron

There are three types of Magnetrons

1) Negative resistance type 2) Cyclotron frequency type

3) Travelling wave or cavity type

1. Negative Resistance Type :

- These are useful only at the frequency less than 500 MHz. These magnetrons uses the negative resistance between two anode segments. The negative resistance magnetrons are capable of generating high power output. The length of the tube plate is limited to few centimetres. The small diameter tube is required to make the magnetron operate efficiently at microwave frequency.

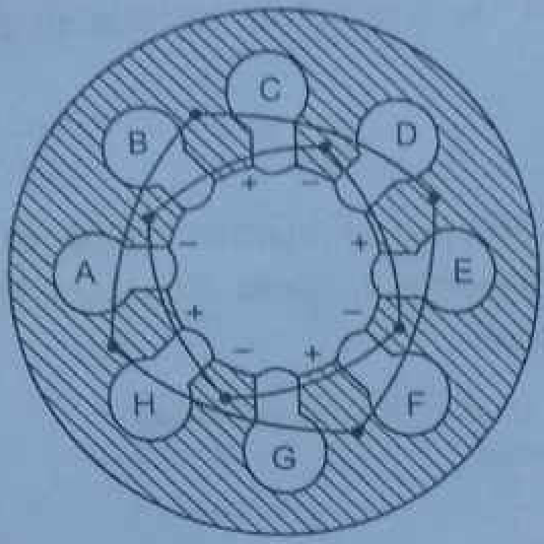
2. Cyclotron Frequency Type

- These are useful only for frequencies greater than 100 MHz. The working of these magnetrons depends upon the synchronisation between an alternating component of electric field and periodic oscillations of electrons in the direction parallel to this field.

3. Travelling Wave or Cavity Type

- These magnetrons provides the oscillations of very high peak power. These are very useful in radar applications. The working of these magnetrons depend upon the interaction of electrons with a rotating electromagnetic field of constant angular velocity. We have already discussed the construction of these magnetrons. In next section we will discuss the operation of cavity magnetrons.

3 Modes of Operation



g. 6.2.9 Strapping alternate segments

- The cavity magnetron shown in Fig. 6.2.9 has 8-cavities. They are tightly coupled to each other. A N-cavity tightly coupled system will have N-modes of operation. Each mode is characterizes by a combination of frequency and phase of oscillation relative to the adjacent cavity. These modes are self consistent so that the total phase shift around the ring of cavity resonators in $2n\pi$, where n is an integer for the 8-cavity magnetron. Minimum phase shift should be 45° ($45 \times 8 = 360^{\circ}$) ($Q_v$).
- The relative phase change of ac electric field across adjacent cavities is given by

$$Q_v = \frac{2\pi n}{N}$$

where $$n = 0, \pm 1, \pm 2, \pm\left(\frac{N}{2}-1\right), \pm\frac{N}{2}$$

$\frac{N}{2}$ mode of resonance can exist if N is an even number

if $n = \frac{N}{2}$, then $Q_v = \pi$

This mode of operation is called **π - mode** If $n = 0$, then $\phi_v = 0$

- This mode of operation is called **zero-mode**. This mode is not used in magnetron operation because there will be no RF electric field between anode and cathode.

.2.3.4 Working of Magnetron

) When there is no RF field in cavity magnetron (zero-mode)

- The strong electric field going from anode to cathode is created by applying the negative voltage pulse to cathode. The strong electric field causes the electrons to accelerate towards the anode after they have been accelerated by the cathode. As we will discussed earlier that the electron takes the energy from field when it is accelerated by electric field and moving against the electric field. An electron gives up energy to field and slows down if it

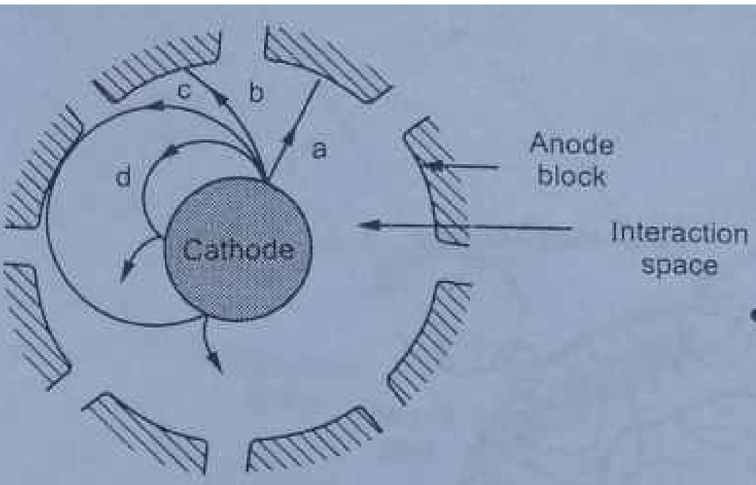


Fig. 6.2.10 Electron trajectories in the presence of crossed electric and magnetic fields. (a) No magnetic field (b) Small magnetic field (c) Magnetic field = B_c (d) Excessive magnetic field

moving in the same direction as the electric field. Oscillations are sustained in the magnetron because of the acceleration and retardation of the electric and magnetic fields.

- In this diagram a, b c and d are four different electrons which exerts different electric and magnetic field (B = 0), the electron travels straight line from cathode to anode due to the radial electric field force action on it. It is the path of electron 'a' in Fig. 6.2.10. If the magnetic field strength is increased slightly, it will exert lateral force on it and it travels from cathode to anode in a small current path of electron 'b' as shown in Fig. 6.2.10 the radius of the path directly varies with electron velocity and inversely proportional to the magnetic field strength. The radius is given by

$$R = \frac{mV}{eB}$$

where m is mass of electron

e is charge on electron

- When magnetic field is increased then the electron does not reach to the anode shown by path of electron 'C' in Fig. 6.2.10 the anode current becomes zero. The magnetic field required to return electrons back to the cathode is called the critical magnetic field (B_{OC}) is also known as **critical magnetic field.**
- If the magnetic field is made larger than the critical field ($B > B_{OC}$), the electron exerts a greater force on it and it returns back to cathode quick faster than the electron C. As shown by path of electron 'd' in Fig. 6.2.10. All such electrons may cause back heating of the cathode. This can be avoided by switching off the heater supply after commencement of oscillation.

ii) When the RF oscillations present in cavity magnetron (π - mode)

- Assume that the RF oscillations are initated due to some noise transient within the magnetron and oscillations are sustained by the device operation. When n = 4 then there is π-mode of operation which is shown in Fig. 6.2.11. The anode poles are π-radians apart in phase.

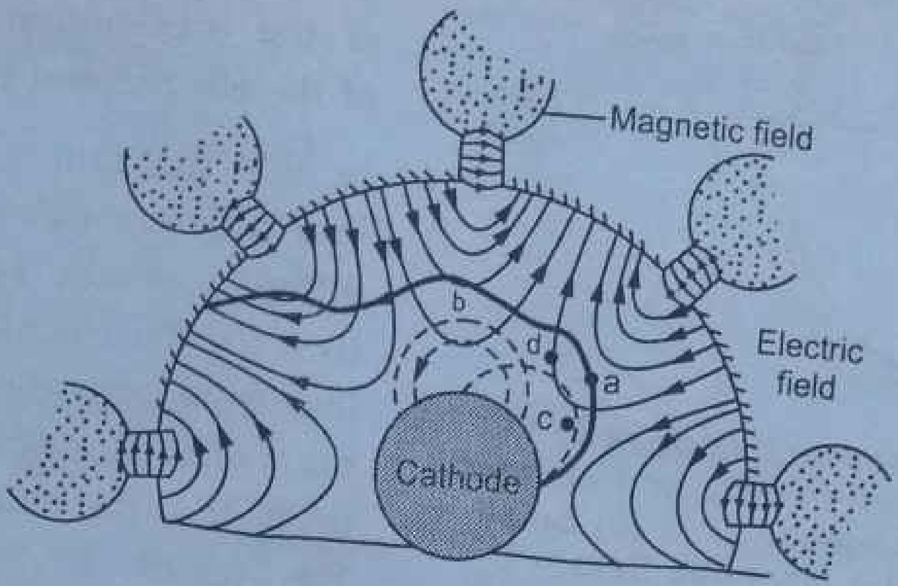


Fig. 6.2.11 π-mode of magnetron

- As shown in Fig. 6.2.11 the electron a is seen to be slow down in the presence of oscillations thus transferring energy from cathode to anode. The electrons which participate is transferring the energy to the RF field are called **forward electrons** and they are responsible for the bunching effect. The electron 'b' is accelerated by the RF field and it takes energy from the oscillations resulting in increased velocity. It bands more sharply spends very little time in interaction space and returned back to cathode, these electrons are unfounded electrons which do not participate in bunching process. The electron 'd' slowed down and it falls back in step with electron a This results in forward electron like a, c, d to form a such and are confined to spokes or electron clouds. The spokes so formed in π-mode rotate with an angular velocity corresponding to two poles per cycle. The process is called phase focussing effect corresponding to a bunch of forward electrons around the reference electrons a. The phase focussing effect of these forward electrons imports enough energy to the RF oscillations so that they are sustained.

.3.5 Magnetron Anode Structure

- Actually anodes have a nearly infinite number of cyclotron frequencies, so are not terribly valuable. In actual microwave magnetrons, a series of cavity resonators is used, each of which behaves like a resonant LC tank circuit as shown in Fig. 6.2.12.

- When an electron cloud sweeps past a resonator, its shock excites the resonator into self-oscillation. This effect is the same as an impulse shock exciting an LC tank circuit. The oscillations combine to set up an electric wave in the interactions space between cathode and anode. Because the wave adds algebraically with the static dc potential, it causes both acceleration and deceleration of the electron cloud. This action, both velocity and density, modulates the cloud, causing it to bunch up into a spoked wheel formation, as shown in Fig. 6.2.18.
- In an oscillating magnetron the spokes of the electron cloud wheel rotate in close synchronism with the wave phase velocity. The electron drift velocity (E/B) must match the phase velocity for sustained oscillations. Under this condition, spokes of the wheel continue to revolve, continually reringing the cavity resonators and creating a sustained wave at a microwave frequency. Because this process causes electrons to lose energy to the wave by interaction, the electrons tend to lose velocity and fall into the cathode, where they are collected. Thus, in the oscillation mode there is no anode current (V > hull potential).
- Oscillation in the pi mode can occur at voltage between a critical level called the **Hartree potential** and the Hull potential. The Hull potential was described previously, the Hartree potential is found from

$$\boxed{V_{Ht} = \frac{2\pi FB}{N}\left(b^2 - a^2\right)}$$

where V_{Ht} = Hartree potential in volts

B = Magnetic field flux density in webers per square meter(Wb/m^2)

F = Oscillating frequency in hertz (Hz)

N = Number of cavity resonators

b = Anode radius in meters (m)

a = Cathode radius in meters (m)

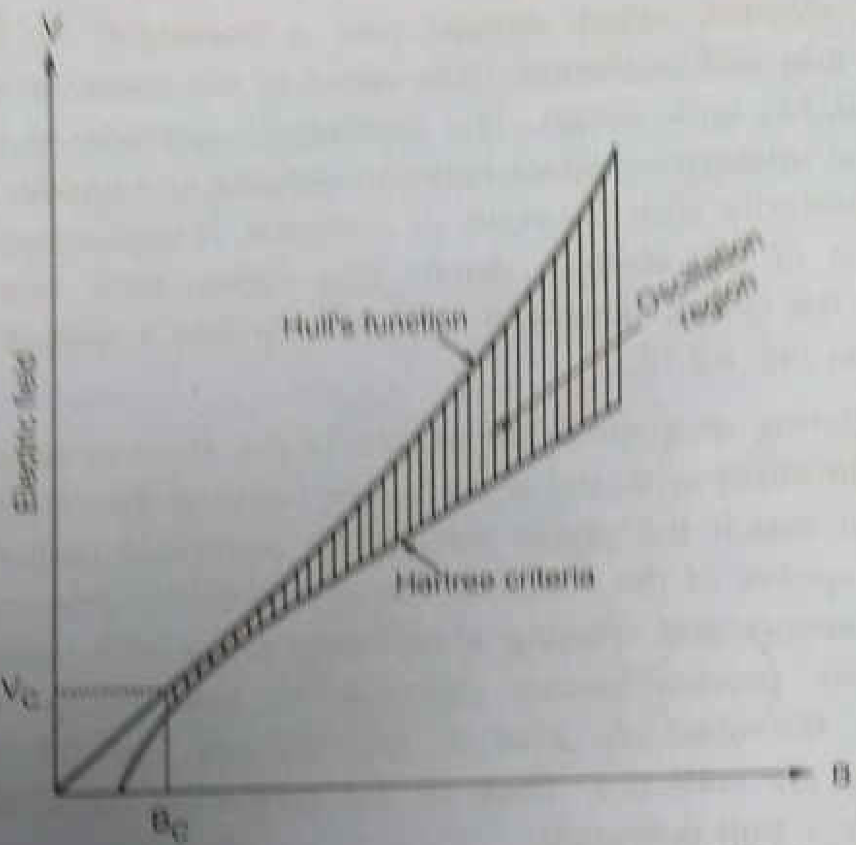


Fig. 6.2.19 Relationship between Hull potential and Hartree potential

6.2.3.9 Phase Focusing Effect

Fig. 6.2.20 Phase focusing

- π - mode oscillations of cavity magnetron causes electron to bunch, but here this effect is known as **phase focusing effect**. Without this effect electrons would fall behind the phase change of the electric field across the gaps, since such electrons are retarded at each interaction with the RF field.
- Fig. 6.2.20 shows the bunched electron clouds rotating around magnetron cathode.
- These bunches rotate counter clockwise with the correct velocity to keep up with RF phase changes between adjoining π mode poles. Thus continued interchange of energy takes place, with the RF field.

6.2.3.10 Cut-off Magnetic Field Density (B_{oc})

- It is the magnetic field strength for a given voltage V_0, which causes the electrons to just graze the anode surface and return towards cathode. It is denoted by B_{oc}.

13 Characteristics of Magnetron

he performance characteristics of magnetron is as follows

1. Efficiency : very high 40 to 70%
2. Power output : 800 kW (pulsed)
3. Operating frequency : upto 10 GHz.

4 Applications of Magnetron

1. Magnetrons are widely used in radars with high output power.
2. In satellite and missiles for telemetry.
3. Industrial heating.
4. Microwave ovens.
5. In oscillators with great power and pulsed operation at 100 GHz and greater