

### Introduction, cross-fields effects:

The tubes discussed earlier (viz. klystron, reflex klystron, TWT and BWO) are linear beam tubes generally called 'O' type tubes (as) original type. The other type of microwave tubes are cross-field tubes in which the electric and magnetic fields are perpendicular to each other.

### Magnetrons- Different Types,

The principal tube in this type, called the M-type or is the magnetron. The magnetron was invented by Hull in 1921 and an improved high power magnetron was developed by Randall and Boot around 1939. Magnetron provide microwave oscillations of very high peak power.

It may be noted in klystrons that the electrons carrying energy are in contact with the RF field in the resonant cavity only for a short duration. However, if the electrons can be made to interact with RF field for a longer duration higher efficiency can be obtained. This has been done in TWT and in magnetron also the same technique is utilised.

They are three types of magnetrons.

1. Negative Resistance type
2. Cyclotron frequency type
3. Travelling wave (as) cavity type.

## 1. Negative Resistance type:

Negative resistance magnetrons makes use of negative resistance but between two anode segments but have to low efficiency are useful only at low frequency ( $< 500 \text{ MHz}$ ).

## 2. cyclotron frequency tube:-

Cyclotron frequency magnetrons depend upon synchronism between an alternating component of electric and periodic oscillations of electrons in a direction parallel to this field. These are useful only for frequencies greater than  $100 \text{ MHz}$ .

## 3. cavity tube (or) Travelling wave tube

Cavity magnetrons depends upon the interaction of electrons with a rotating electro-magnetic field of constant angular velocity. This provide oscillations of very high peak power and hence are very useful in radar applications.

### Cylindrical Travelling wave magnetron.

#### Cavity magnetron:-

It is a diode usually a cylindrical configuration with a thick cylindrical cathode at the centre an a coaxial cylindrical blocks of copper as anode.

- \* In anode block are cut a number of holes and slots which act as resonant anode cavities.
- \* The space between the anode and cathode is the interaction space and to one of the cavities is connected a coaxial line or waveguide for extracting output.
- \* It is a cross-field device as the electric field between anode and cathode is the radial.

\* whereas the magnetic field produced by permanent magnet is axial.

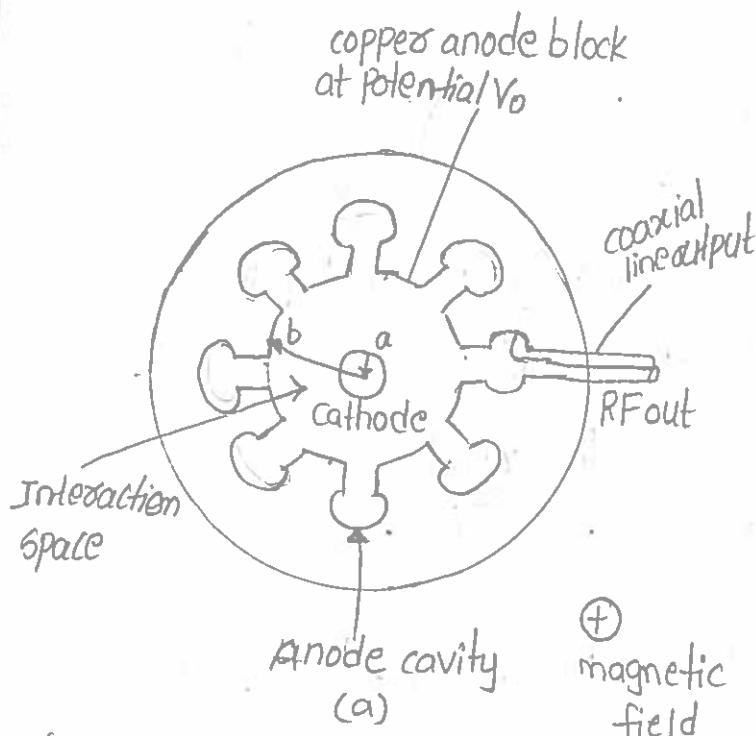


fig: constructional detail of cavity magnetron.

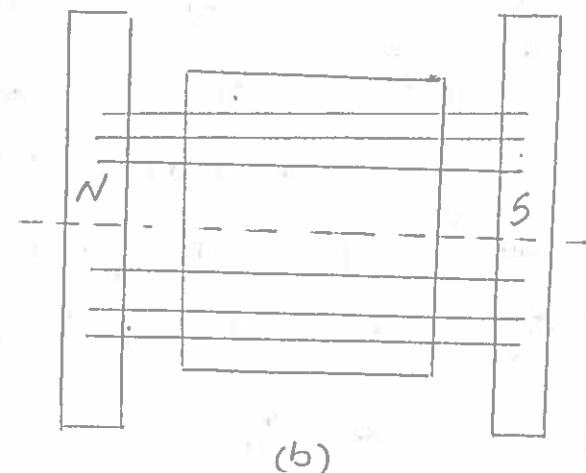


fig: magnetic flux lines in magnetron.

\* The permanent magnet is placed such that the magnetic lines are parallel to the vertical cathode and perpendicular to the electric field between cathode and anode. The construction is shown in fig (a) & fig (b).

### operation

\* The cavity magnetron shown in fig (a) has 8 cavities that are tightly coupled to each other.

We know, in general that a  $N$ -cavity tightly coupled system will have  $N$ -modes of operation each of which is uniquely characterised by a combination of frequency and phase of oscillation relative to adjacent cavity.

- \* In addition, these modes must be self consistent so that the total phase shift around the ring of cavity resonators is  $2n\pi$  where  $n$  is an integer.
- \* For example, a phase shift should be  $40^\circ$  between cavities of 8-cavity magnetron will mean that the first cavity is out of phase with (velocity) itself by  $320^\circ$ ! The correct minimum phase shift should be  $45^\circ$  ( $45 \times 8 = 360^\circ$ ).
- \* Therefore If  $\phi_V$  represents the relative phase changes of the ac electric field across adjacent cavities, then.

\* 
$$\phi_V = \frac{2\pi n}{N}$$
 where  $n = 0, \pm 1, \pm 2, \pm \left[\frac{N}{2} - 1\right], \pm \frac{N}{2}$

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

\* If  $n = \frac{N}{2}$ ,  $\phi_V = \pi$

this mode of resonance is called the  $\pi$ -mode

\* If  $n = 0$   $\phi_V = 0$

This is Zero-mode, meaning there will be no RF electric field between anode and cathode called the fringing field and no use of in magnetron operation.

### Hull cut-off and Haarée conditions

All the above explanation is for static case in the absence of the RF field in the cavity of magnetron.

- \* Assuming RF oscillations to have been initiated due to some noise transient within the magnetron, the oscillations sustained by device operation.
- \* As pointed out earlier self consistent oscillations will be obtained if the phase difference between adjacent anode poles is  $\frac{n\pi}{4}$ , where  $n$  is an integer.  $n=4$  results in  $\pi$ -mode of operation, which as shown fig (a).

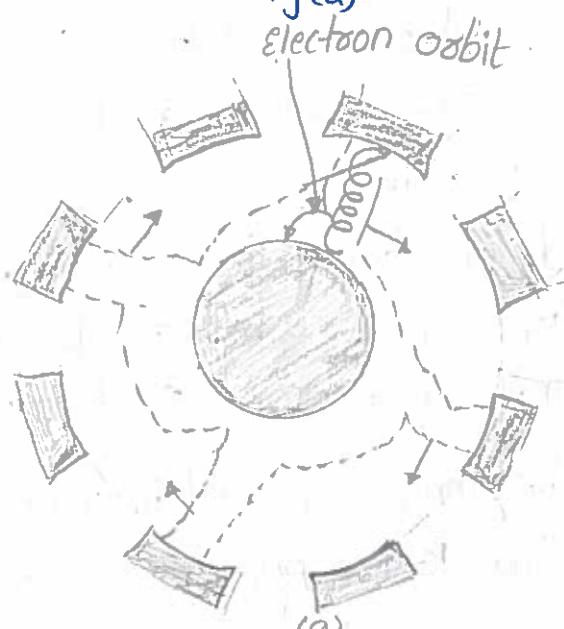


fig: (a) phase focussing effect

- \* Here anode poles are  $\pi$  radians. a part of phase. the dotted electron paths refers to the case of static fields with no RF field.
- \* The solid paths refers to the electron trajectories in the presence of RF oscillations. in the interaction space.
- \* The electron 'a' is seen to be slowed down in presence of oscillations thus transferring Energy to the oscillations, during its longer journey from cathode to anode.
- \* Such electrons which participate in transferring energy to RF field are called favoured electrons and are responsible for bunching - effect.
- \* An electron 'b' is accelerated by RF field and instead of imparting energy to the oscillations takes energy

- \* from oscillations resulting in increased velocity. Hence bends more sharply, spends very little time in the interaction space and is returned back to the cathode. such electrons are called unfavoured electrons. which do not participate in the bunching process rather they are harmful in the sense by they cause back heating.
- \* Similarly 'c' an electron which is emitted a little later to be in correct position moves faster and tries to catch up with electron 'a' and an electron emitted at 'd' will be slowed down fall back in step with electron 'a'!
- \* This results in all favoured electrons like 'a', 'c', 'd', to form a bunch and are confined to spokes or electron clouds
- \* one of for each to a bunch of favoured electrons around the reference electron 'a'. The spokes so formed in  $\pi$ -mode rotate with angular velocity corresponding to two poles per cycle.
- \* The phase focussing effect of these favoured electrons imparts enough energy to the RF oscillations so they are sustained.

### Mathematical analysis.

cylindrical magnetron being the most commonly used magnetrons, we will deal with us mathematical analysis rather than parallel plate magnetron which is not very commonly used.

- let the cathode and anode radius be 'a' and 'b' respectively and  $\phi$  the angular displacement of the electron bends. Being a cross field device electric and magnetic fields. are perpendicular to each other and the path of the electron in the presence of this cross field is naturally parabolic.

In this fig (b).

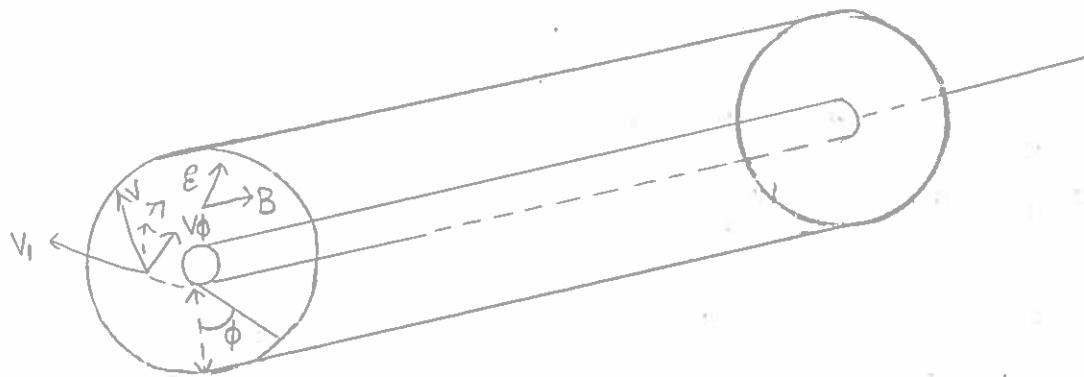


Diagram for analysis of cylindrical magnetron

Force acting on the electron is

$$F = Bev$$

In the direction of  $\phi$ , the force component  $F_\phi$  is given by

$$F_\phi = eBv_p$$

where  $v_p$  = velocity in the direction of the radial distance  $\rho$  from the centre of the cathode cylinder. Torque in  $\phi$  direction is

$$T_\phi = \rho F_\phi = e\rho v_p B \rightarrow ①$$

Angular momentum = angular velocity  $\times$  moment of inertia.

$$\frac{d\phi}{dt} = \omega$$

$$\frac{d\phi}{dt} = \frac{d\theta}{dt} \rho^2$$

$$\text{Time rate of angular momentum} = \frac{d}{dt} \left[ \frac{d\phi}{dt} \times \rho \rho^2 \right] \rightarrow ②$$

which gives the torque in  $\phi$  direction.

Eqn ① and ② (the two are values of torque in  $\phi$  direction).

$$\frac{d}{dt} \left[ \left( \frac{d\phi}{dt} \right) \rho \rho^2 \right] = e \cdot \rho \cdot v_p \cdot B$$

$$2\rho \frac{d\phi}{dt} + \rho \rho^2 \frac{d^2\phi}{dt^2} = e \cdot \rho \cdot v_p \cdot B \rightarrow ③$$

We know that

$$v_p = \frac{dr}{dt}$$

$$\rho v_p = \rho \cdot \frac{dr}{dt}$$

$$\int p \cdot \frac{dp}{dt} = \frac{p^2}{2}$$

Integrating eqn ③ with respect to 't'

$$2mp \cdot \phi + mp^2 \cdot \frac{d\phi}{dt} = eB \cdot \frac{p^2}{2}$$

For a particular direction  $\phi$ ,  $mp\phi$  can be thought of as a constant.

$$mp^2 \frac{d\phi}{dt} + c = eB \cdot \frac{p^2}{2} \rightarrow ④$$

Now applying boundary conditions (i.e. at surface of the cathode  $p=a$

and  $\frac{d\phi}{dt}=0$  being zero angular velocity at emission), we can determine the value of constant 'c'

$$0+c = \frac{e \cdot B \cdot a^2}{2} \text{ or } c = \frac{eBa^2}{2}$$

substituting the value of c in eqn ④ we get

$$mp^2 \frac{d\phi}{dt} = \frac{eB^2}{2} (p^2 - a^2)$$

$$\frac{d\phi}{dt} = \frac{eB}{2m} \left\{ 1 - \frac{a^2}{p^2} \right\}$$

when  $p=a$ , (i.e., at cathode),  $\frac{d\phi}{dt}$  approaches 0.

and when  $p \gg a$ ,  $\frac{d\phi}{dt}$  approaches  $(\omega)_{\max}$  (maximum angular velocity)

$$\text{i.e., } \left( \frac{d\phi}{dt} \right)_{\max} = (\omega)_{\max} = \frac{eB}{2m} = \frac{eBc}{2m} \rightarrow ⑤$$

where  $B=B_c$  is the cut off magnetic flux density

We know that from conservation of energy that potential energy of electron = kinetic energy of electron.

$$\text{i.e. } eV_0 = \frac{1}{2}mv^2$$

$$eV_0 = \frac{m}{2} (v_p^2 + v_\phi^2) \rightarrow ⑥$$

where  $v_p$  and  $v_\phi$  are components in  $\rho$  and  $\phi$  directions in cylindrical co-ordinates

$$v_p = \frac{dp}{dt} \quad \text{and} \quad v_\phi = \rho \cdot \frac{d\phi}{dt}$$

Rewrite the eqn ⑥ (substituting for  $v_p$  and  $v_\phi$ ),

$$eV_0 = \frac{m}{2} \left[ \left( \frac{dp}{dt} \right)^2 + \rho^2 \left( \frac{d\phi}{dt} \right)^2 \right]$$

from eqn ⑤

$$\left( \frac{d\phi}{dt} \right) = (\omega)_{\max} \left[ 1 - \frac{a^2}{\rho^2} \right]$$

$$eV_0 = \frac{m}{2} \left[ \frac{dp^2}{dt} + \rho^2 (\omega)_{\max}^2 \left[ 1 - \frac{a^2}{\rho^2} \right]^2 \right] \rightarrow ⑦$$

At anode  $\rho = b$   $\frac{dp}{dt} = 0$  substituting these boundary condition in eqn ⑦

$$\frac{m}{2} \left[ b^2 \cdot (\omega)_{\max}^2 \left[ 1 - \frac{a^2}{b^2} \right] \right] = eV_0 \rightarrow ⑧$$

$$(\omega)_{\max}^2 = \left( \frac{eB_c}{2m} \right)^2 \text{ from eqn ⑤}$$

where  $B_c$  is the cut-off value of the magnetic flux density substituting in eqn

$$D_2 = j \frac{V_0^2}{wp^2 \omega} (B - B_0)^2 J_2$$

$$\frac{m}{2} b^2 \left( \frac{eB_c}{2m} \right)^2 \times \left[ 1 - \frac{a^2}{b^2} \right] = eV_0$$

$$\boxed{\frac{e^2 B_c^2 b^2}{8m} \left[ 1 - \frac{a^2}{b^2} \right]^2 = eV_0}$$

$$\boxed{B_c = \left[ \frac{8V_0 m}{e} \right]^{\frac{1}{2}} \left[ \frac{1}{b \left[ 1 - \frac{a^2}{b^2} \right]} \right]^{\frac{1}{2}}}$$

since  $b \gg a$  and  $\frac{b^2}{b^2}$  can be neglected.

$$B_c = \frac{1}{b} \sqrt{\frac{8mV_0}{e}} \rightarrow \textcircled{9} \text{ Hull-cut off voltage}$$

At this cut-off value of magnetic field, the electron grazes the anode and (cathode) the value of this magnetic field can be obtained by the knowledge of anode voltage. eqn \textcircled{9} is called Hull-cut off voltage equation.

### Modes of Resonance and PI-mode operation & Separation of TI-Mode

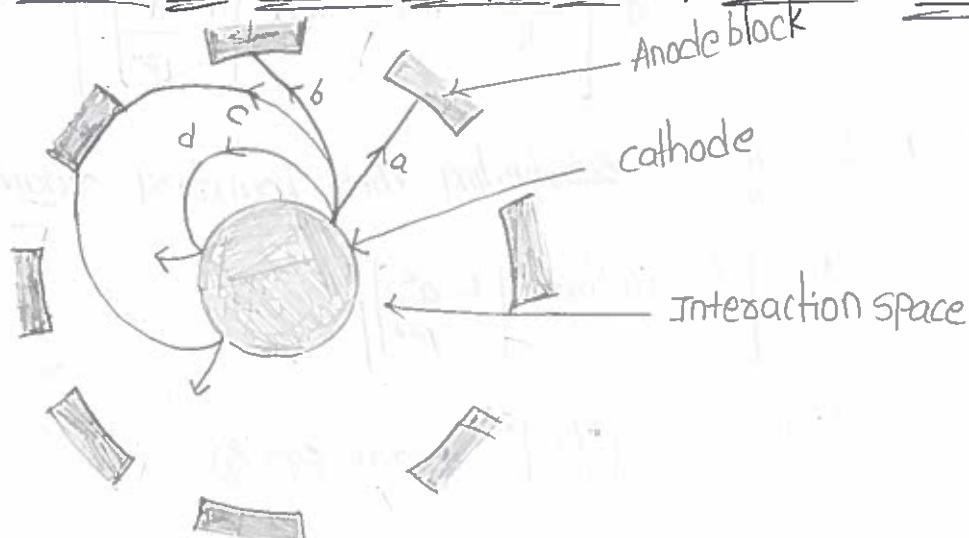


fig Electron trajectories in the presence of crossed electric and magnetic field (a) no magnetic field (b) small magnetic fields (c) magnetic field =  $B_c$  (d) excessive magnetic field.

- \* To understand the operation of cavity magnetron, we must first look at how the electrons behave in the presence of crossed electric and magnetic field
- \* Depending on the relative strengths of the electric and magnetic fields, the electrons emitted from cathode (to anode) and moving towards the anode with traverse

- \* through the interaction space as shown in fig(a)

In the absence of magnetic field ( $B=0$ ), the electron travels straight from the cathode to anode due to the radial electric field force acting on it. (indicated by the trajectory 'a' in fig (a))

\* If the magnetic field strength is increased slightly (i.e. for moderate value of  $B$ ) It will exert a lateral force bending the path of electron as shown by path 'b' in fig(a)

\* The radius of the path is given by  $R = \frac{mv}{eB}$ , that varies directly with electron velocity and inversely as the magnetic field strength.

- \* if the strength of the magnetic field is made sufficiently high so as to prevent the electron from reaching the anode (as shown by path 'c' and those inside in fig (b)) the anode current becomes zero.

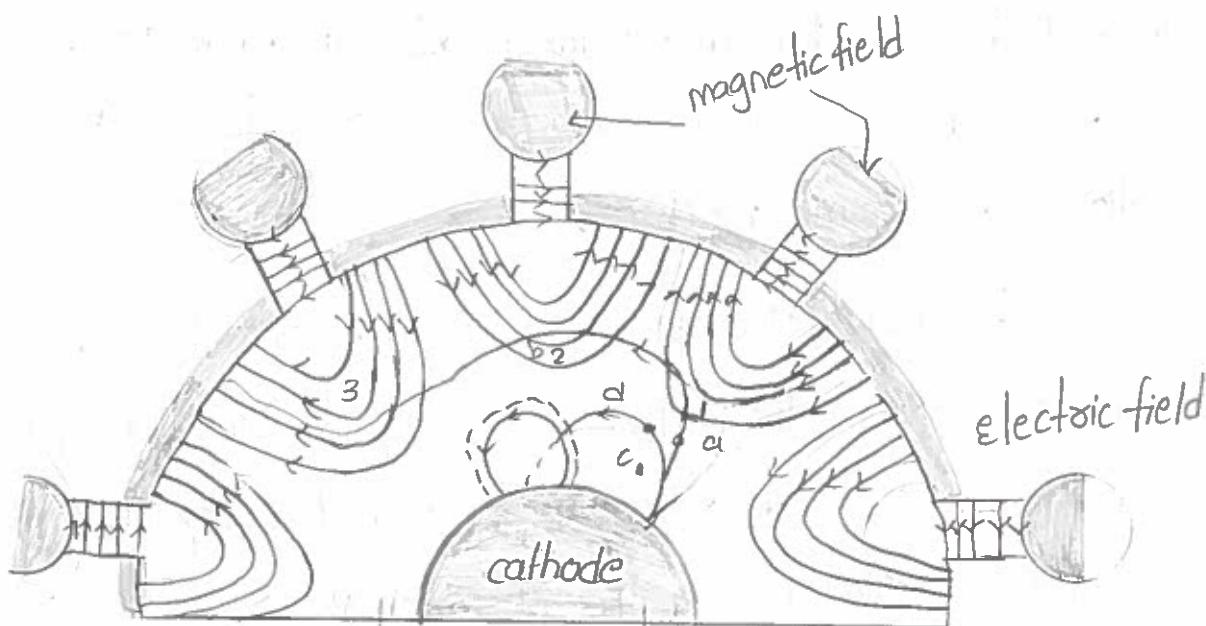


fig: Tilted Mode of magnetron  
(b)

- \* The magnetic field required to return electrons back to cathode just grazing the surface of the anode is called critical magnetic field ( $B_c$ ), the cut-off magnetic field.

- \* If the magnetic field is made larger than critical field ( $B > B_c$ ), the electron experiences a greater rotational force and may return back to cathode quite faster.
- \* All such electrons may cause back heating of the cathode this can be avoided by switching off the heater supply after commencement of oscillation. This done to avoid fall in the emitting efficiency of the cathode.
- \* At the above explanation is for a static case in the absence of the RF field in the cavity of magnetron. Assuming
  - \* RF oscillations emitted to have been initiated due to some noise transient within the magnetron, the oscillations will be sustained by device operation.
  - \* As the pointed out earlier self consistent oscillations can be obtained if the phase difference between adjacent anode poles is  $n\pi/4$  where  $n$  is an integer where  $n=4$  results in  $\pi$  mode operation. as shown in fig (b).
  - \* Here the anode poles are  $\pi$  radians apart in phase.
- \* The dotted electron paths refers to the case of static fields with no RF field. The solid paths refers to electron trajectories. in the presence of RF oscillations. in the interaction space.
- \* The electron 'a' is seen to be slowed down. in presence of oscillations thus transferring energy to the oscillations during its longer journey from cathode to anode. such electrons participating in transferring energy to the RF field is called favoured. Electrons are responsible for bunching - effect.

An electron 'b' is accelerated by the RF field and instead of impacting energy to the oscillations takes energy [to RF field] x

\* Take Energy from oscillations resulting in increased velocity. Hence bends more sharply, spends very little time in the interaction space and is returned back to cathode. such electrons called "un favoured electrons" which is not participate in bunching process rather than they are harmful in the sense by the cause back heating.

\* Similarly an electron 'c' which is emitted a little later to be in a correct position moves faster and tries to catch up with electron 'a' These results in all favoured electrons like a, c, d to form bunch and are confined to spokes or electron clouds.

one for each two anodes as shown in fig(b) The process is called "Phase focussing effect" corresponding to a bunch a favoured electrons around the reference electron 'a'.

\* The spokes so formed in the  $\pi$ -mode rotate with angular velocity corresponding to  $\pi$  two poles per cycle.

\* The phase focussing effect of these favoured electrons imparts enough energy to the RF oscillations so that they are sustained.

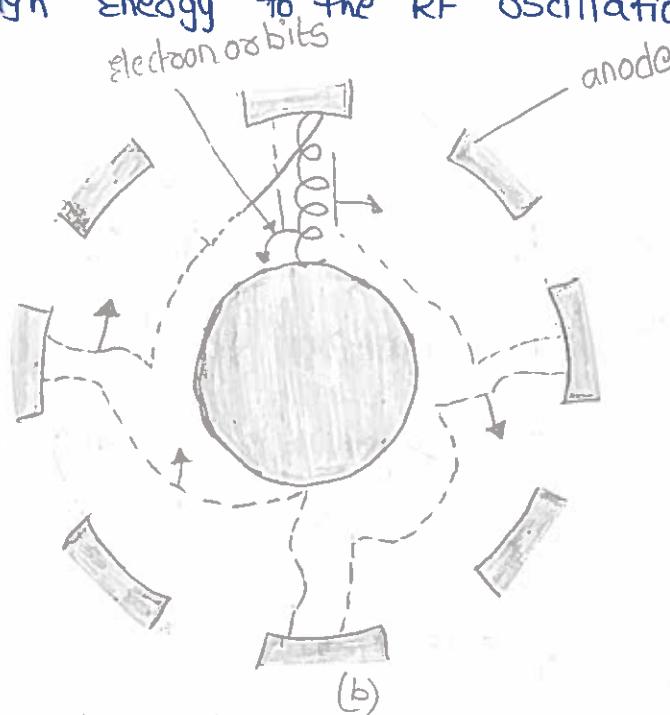


fig:- phase focussing effect

## output characteristics,

Performance characteristics of magnetron.

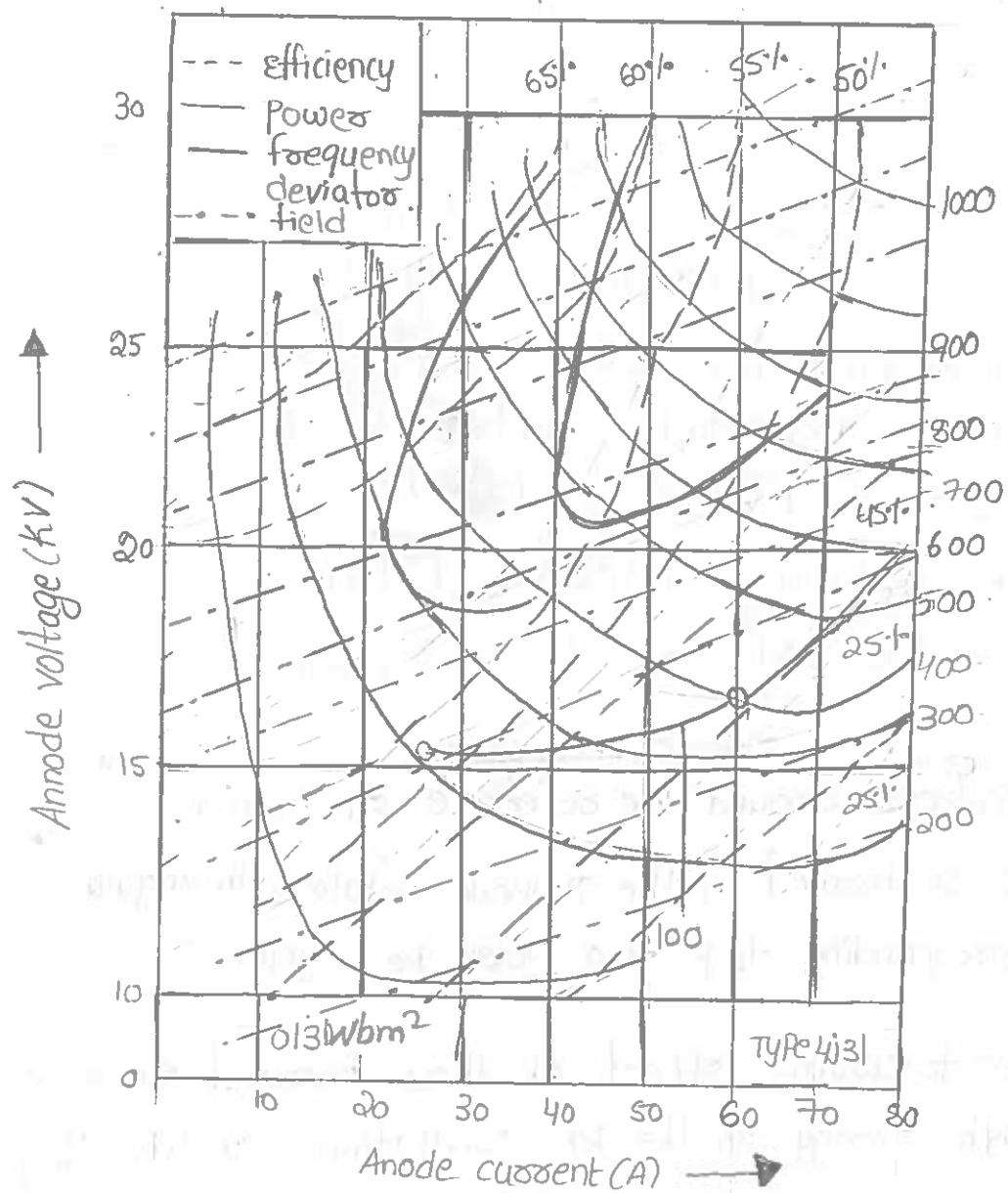


fig:- Rieke diagram performance chart of magnetron.

These are best studied by means of Rieke diagram fig (a) the operating conditions of magnetron for given load can be obtained from these diagram which is basically a plot of anode voltage vs current with power output, efficiency, flux density, frequency deviation as parameter. The frequency pushing & pulling effects can be easily determined from this diagram.

## Performance characteristics:-

1. Power output :- In excess of 250 kW (pulsed mode)  
10mW (UHF band) 2mW (Xband)  
8kW (at 95 GHz)
2. Frequency :- 500 MHz to 12 GHz
3. Duty cycle :- 0.1 %
4. Efficiency :- 40% to 70%

## Applications of magnetron

1. The pulsed radar is the single most important application with large pulse powers.
2. Voltage Tunable magnetrons (VTM's) are used in sweep oscillations in telemetry and in missile applications. (200 MHz to X band with CW powers upto 500 W,  $\eta$  of 70%)
3. Fixed frequency, CW (Continue wave) magnetrons are used for Industrial heating and microwave ovens (500 MHz - 2.5 GHz frequency range, 500W to 10 kW power outputs,  $\eta$  of 50%)

## Important Formula:-

cavity klystron Amplifier.

$$\text{Electron velocity } V_0 = \sqrt{\frac{2eV_0}{m}} = 0.593 \times 10^6 \sqrt{V_0}$$

$$\text{Gap transit angle, } \theta_g = \omega \frac{d}{V_0}$$

$$\text{Beam - coupling coefficient, } \beta_i = \frac{\sin(\theta_g/2)}{\theta_g/2}$$

$$\text{dc transit angle between cavities, } \theta_0 = \frac{\omega L}{V_0}$$

$$\text{Bunching parameters, } x = \frac{\beta_i V_i}{2V_0} \theta_0$$

$$\text{Input voltage, } V = \frac{2V_0}{\beta_0 \theta_0} x$$

$$\text{Voltage gain } A_V = \frac{|V_2|}{|V_1|} = \frac{B_0 I_2 V_2}{V_1} = \frac{B_0^2 \phi_0 J_1(X)}{R_0 X} R_{sh}$$

$$\text{Efficiency } = \frac{P_{out}}{P_{in}} = \frac{B_0 I_2 V_2}{2 I_0 V_0} = \frac{0.58 V_0}{V_0}$$

Electron gain voltage of anode for maximum power transfer.

$$= \left[ \frac{V_1}{V_0} \right]_{max} = \frac{3.68}{2n\pi - \pi/2}$$

### Multicavity Klystron Amplifier:

charge density,  $\rho = B \cos(B_c z) \cos(\omega_q t + \theta)$

velocity perturbation,  $v = -C \sin(B_c z) \sin(\omega_q t + \theta)$

where  $B$  = constant of charge-density perturbation

$C$  = constant of velocity perturbation.

$B_0 = \frac{\omega}{V_0}$  is the d.c. phase constant of electron beam

$\omega_q = R_c \omega_p$  is the perturbation frequency of reduced plasma frequency

$R_c$  = the space charge reduction factor

$\omega_p = \sqrt{\frac{e \rho_0}{m_e}}$  is the plasma frequency

$\theta$  = phase angle of oscillations

Instantaneous convection beam-current density

$$J_{tot} = J_0 + J$$

$$J = \rho v_0 - \rho_0 v$$

$$J_0 = \rho_0 v_0$$

Output current and power to two-cavity klystron

$$I_2 = \frac{1}{2} \frac{I_0 w}{V_0 \omega_q} B_0^2 |V_1|$$

$$P_{out} = |I_2|^2 R_{sh} = \frac{1}{4} \left[ \frac{I_0 w}{V_0 \omega_q} \right]^2 B_0^4 |V_1|^2 R_{sh}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{J_0 V_0} = \frac{1}{4} \left[ \frac{I_0}{V_0} \right] \left[ \frac{V_1 w}{V_0 \omega_q} \right]^2 B_0^4 R_{sh}$$

output current and power of four cavity klystron

$$|I_4| = \frac{1}{8} \left( \frac{I_0 w}{V_0 w_0} \right)^2 B_0^6 / V_1 / R_{sh}^2$$

$$P_{out} = |I_4|^2 R_{sh} = \frac{1}{64} \left( \frac{I_0 w}{V_0 w_0} \right)^6 B_0^{12} / V_1^2 R_{sh}^2$$

$R_{sh}$  = total shunt resistance of the output cavity including the external load

### ① Example:

A four cavity klystron VA - 628 has the following parameters.

Beam voltage :  $V_0 = 14.5 \text{ kV}$

Beam current :  $1.4 \text{ A}$

operation frequency :  $f = 10 \text{ GHz}$

dc electron charge density  $\rho_0 = 10^6 \text{ c/m}^3$

RF charge density  $\rho = 10^8 \text{ c/m}^3$

velocity perturbations  $v = 10^5 \text{ m/sec.}$

compute the

- (i) dc velocity electron, (ii) the dc phase constant, (iii) the plasma frequency in the reduced plasma frequency for  $R=0.4$  (iv) The dc beam current density
- (v) The instantaneous beam current density

### Solution

$$\begin{aligned} \text{(i) The dc electron velocity } v_0 &= 0.593 \times 10^6 \sqrt{V_0} \\ &= 0.593 \times 10^6 \sqrt{14.5 \times 10^3} \\ &= 0.774 \times 10^8 \text{ m/sec.} \end{aligned}$$

$$\begin{aligned} \text{(ii) the dc phase current} &= \frac{\omega_0}{V_0} \frac{2\pi \times 10 \times 10^9}{0.774 \times 10^8} \\ &= 1.41 \times 10^8 \text{ aod/sec} \end{aligned}$$

(iii) the plasma frequency

$$\begin{aligned} \omega_p &= \left[ 1.759 \times 10^{11} \times \left[ \frac{\text{dc electron charge density}}{\epsilon_0} \right] \right]^{1/2} \\ &= \left[ 1.759 \times 10^{11} \times \left[ \frac{10^{-6}}{8.854 \times 10^{-12}} \right] \right]^{1/2} \end{aligned}$$

$$\omega_p = 1.41 \times 10^8 \text{ rad/sec}$$

(IV) The deduced plasma frequency for  $R=0.4$  is

$$\omega_q = 0.4 \times \omega_p = 0.4 \times 1.41 \times 10^8 \text{ rad/sec}$$

$$\omega_q = 0.564 \times 10^8 \text{ rad/sec}$$

(V) The dc beam current density

$$J_0 = P_0 \cdot V_0 = 10^6 \times 0.714 \times 10^8 \text{ m/A}$$

$$J_0 = 71.4 \text{ A/m}^2$$

(VI) The instantaneous beam current density

$$J = 10^6 \times 0.714 \times 10^8 + 10^6 \times 10^5$$

$$J = 0.814 \text{ A/m}^2$$

### Example ②

A two cavity klystron amplifier has voltage gain = 15 dB, input power = 5 mW

$R_{sh}$  of input cavity = 30 k $\Omega$ ,  $R_{sh}$  of output cavity = 40 k $\Omega$   $R_L$  (load impedance) = 40 k $\Omega$

Determine (i) the input rms voltage, (ii) the output rms voltage, (iii) the power delivered to the load.

$$(i) P_{in} = \frac{V_i^2}{R} \text{ (or) } V_i^2 = P_{in} \times R_{sh} \text{ (Input)} = 5 \times 10^{-3} \times 30 \times 10^3 = 150$$

$$V_i = 12.25 \text{ V}$$

$$(ii) A_V = 20 \log \frac{V_o}{V_i} \text{ dB}$$

$$15 = 20 \log \frac{V_o}{12.25} \text{ or } V_o = 68.89 \text{ V}$$

$$(iii) P_{out} = \frac{V_o^2}{R_{sh}} = \frac{(68.89)^2}{20 \times 10^3} = \frac{4745.83}{20 \times 10^3}$$

$$= 0.2373 \text{ W (or) } 237.3 \text{ mW}$$

### Example ③

A reflex klystron operates at the peak mode  $n=2$  with beam voltage

$V_0 = 300 \text{ V}$  Beam current  $I_0 = 20 \text{ mA}$ , Signal voltage  $V_1 = 40 \text{ V}$ . Determine

(i) the input power in watts (ii) output power in watts (iii) efficiency.

$$(i) P_{dc} \text{ (input power)} = V_0 \cdot I_0 = 300 \times 20 \times 10^{-3} = 6 \text{ W}$$

$$(ii) P_{ac} \text{ (output power)} = \frac{2V_0 I_0 \times J_1(X)}{2n\pi - \pi/2} = \frac{2 \times 6 \times 1.25}{2 \times 2 \times \pi - \pi/2} = 1.36 \text{ watts}$$

$$(iii) \eta = \frac{P_{ac}}{P_{dc}} \times 100 = \frac{1.36}{6} \times 100 = 22.7\%$$

**Example (4)** A two cavity klystron Amplifier has Beam voltage:  $V_0 = 900V$   
 Beam current  $I_0 = 30 \text{ mA}$  frequency  $f = 8 \text{ GHz}$  Gap spacing in either cavity  
 $d = 1 \text{ mm}$  cavity space between centre of cavities  $L = 4 \text{ cm}$  Effective shunt  
 Impedance  $R_{sh} = 49 \text{ G}\Omega$ . Determine (a) the electron velocity (b) the dc transit  
 time of electron, (c) the input voltage for maximum o/p voltage (d) the voltage  
 gain in decibels.

Sol (a) electron velocity  $v_0 = 0.593 \times 10^6 \sqrt{V_0}$   
 $= 0.593 \times 10^6 \sqrt{900}$   
 $\boxed{v_0 = 17.79 \times 10^6 \text{ m/sec}}$

(b) dc transit time of electrons

$$\theta_0 = \omega T_0 = \omega \frac{L}{v_0}$$

$$T_0 = \frac{L}{v_0} = \frac{4 \times 10^{-2}}{17.79 \times 10^6} = 0.225 \times 10^{-8} \text{ sec}$$

(c) maximum input voltage

$$V_1(\max) = \frac{V_0 \times 3.68}{B_0 \theta_0}$$

$$\theta_0 = \omega T_0 = 2\pi \times 8 \times 10^9 \times 0.225 \times 10^{-8} = 113.1 \text{ rad}$$

$$B_0 = \sin \theta_0 / \theta_0 / 2$$

$$\theta_g = \omega \frac{d}{v_0} = \frac{2\pi \times 8 \times 10^9 \times 10^{-3}}{17.79 \times 10^6} = 2.825 \text{ rad}$$

$$\theta_g/2 = 1.413 \text{ rad}; \sin \theta_g/2 = 0.988$$

$$B_0 = B_i = \sin \frac{(\theta_g/2)}{\theta_g/2} = \frac{0.988}{1.413} = 0.699$$

$$V_1(\max) = \frac{900 \times 3.68}{0.699 \times 113.1} = 41.894 \text{ Volts}$$

(iv) voltage gain

$$A_\delta = V_0/V_1 = \frac{B_0^2 \theta_0 \left[ \frac{J_1(X)}{X} \right]}{R_{sh}} R_{sh}$$

$$= \frac{(0.699)^2 \times (113.1) (0.582) 40 \times 10^3}{30 \times 10^3 \times 1.841}$$

$$\boxed{A_\delta = 93.293}$$

Example ⑤ The parameters of two cavity amplifier klystron are  
 $V_0 = 1200V$   $I_0 = 22mA$   $f = 8GHz$  Gap spacing in either cavity  $d = 1mm$   
 Spacing between two cavities  $s$ ;  $L = 4cm$  Effective shunt Resistance  $R_{sh} = 40k\Omega$   
 (Excluding beam loading) (a) find the input microwave voltage  $V_i$  in order to generate maximum output voltage (b) determine the voltage gain (reflecting beam loading in the output cavity) (c) calculate the efficiency of amplifier neglecting beam loading. (d) Compute the beam reading conductance and show that one may neglect it in the preceding calculations.

$$(a) \left(\frac{V_i}{V_0}\right)_{max} = \frac{3.68}{2\pi\pi - \pi/2}$$

$2\pi\pi - \pi/2 = \theta_0$  = transit angle between cavities

$$= \omega \frac{L}{v_0} = \frac{2\pi \times 8 \times 10^9 \times 10^{-3} \times 4}{0.593 \times 10^6 \sqrt{1200}} \\ = 97.88$$

$$(V_p)_{max} = \frac{1200 \times 3.68 \times 0.593 \times 10^6 \sqrt{1200}}{2\pi \times 8 \times 10^9 \times 10^{-3} \times 4} = 40 \text{ Volts}$$

If beam amplifying coefficient  $B_i$  is considered

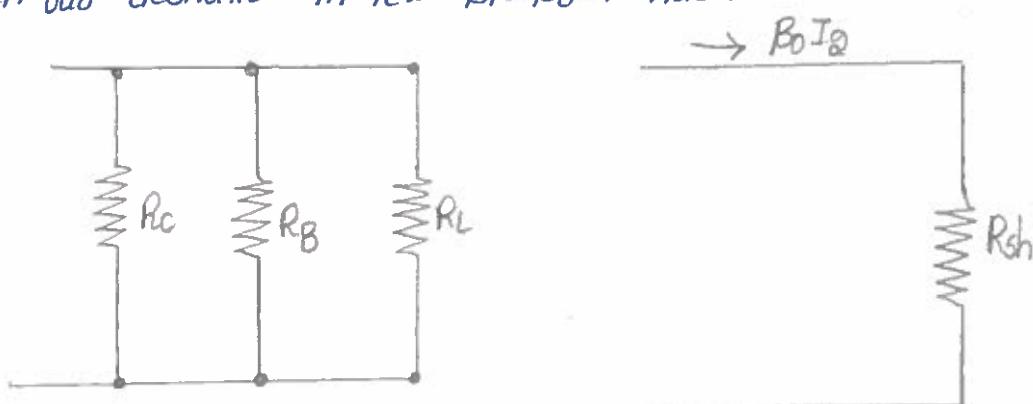
$$B_i = B_0 = \frac{\sin(\theta_0/2)}{\theta_0/2}$$

$$\theta_0/2 = \omega d/v_0 = \frac{2\pi \times 8 \times 10^9 \times 10^{-3}}{0.593 \times 10^6 \sqrt{1200}} = 8.45 \text{ rad}$$

$$B_i = \frac{\sin(8.45/2)}{8.45/2} = 0.768$$

$$V_i(\max) = \frac{46}{0.768} = 58.59 \text{ Volts}$$

In our derivation in text  $B_i = B_0 = 1$  has been assumed.



(b) Voltage gain of klystron amplifier.

$$AV = \frac{V_2/V_1}{V_1} = \frac{B_0 I_2 R_{sh}}{V_1}$$

$$V_1 = \frac{2V_0 X}{B_0 R_0}$$

$$I_2 = 2 I_0 J_1(X)$$

If the beam coupling coefficient of buncher  $B_1$  and catcher  $B_0$  are equal i.e.  $B_0 = B_1$

$$AV = \frac{B_0 \cdot 2 I_0 \cdot J_1(X)}{e V_0 X} B_0 R_0 R_{sh}$$

$$\frac{B_0^2}{R_0} \cdot \frac{J_1(X)}{X} B_0 R_{sh}$$

$R_c$  = Resistance of wall of catcher cavity

$R_B$  = Beam loading resistance

$R_L$  = External load resistance.

$$AV = \frac{(0.768)^2 \times 97.88 \times 0.582 \times 40 \times 10^3}{1200} \\ 28 \times 10^3 \times 1.841$$

$$J_1(X) = 0.582$$

$\therefore X = 1.841$  for maximum  $V_2$

$$AV = 17.034$$

(c) Efficiency =  $\eta = 0.58 \times \frac{V_2}{V_0}$

$$V_2 = B_0 I_2 R_{sh}$$

$$B_0 I_2 = 2 \times 28 \times 10^3 \times 0.582 \times 0.768 \times 40 \times 10^3$$

$$\eta = 0.58 \times \frac{100.23}{1200} = 48.9\%$$

(d) Beam loading conductance

$$G_B = \frac{G_0}{2} \left( B_0^2 - B_0 \cos \frac{\theta_g}{2} \right)$$

$$23.3 \times 10^{-6} \left[ (0.768)^2 - (0.768) \cos (2.45) \right]$$

$$\text{beam loading resistance } R_B = \frac{1}{G_B} = 0.073 \times 10^6 = 73 \text{ k}\Omega$$

The value  $73 \text{ k}\Omega$  is very much comparable to  $R_{sh}$  and cannot be neglected because  $\theta_g$  is quite high

Example 6. A reflex klystron operates under the following conditions

$V_b = 500V$   $R_{sh} = 20k\Omega$   $f_0 = 8GHz$   $L = 1mm$  spacing between deflector and cavity. This tube is oscillating at  $f_0$  at the peak on.  $n = 2$  mode or  $\frac{3}{4}$  mode. Assume the transit time through the gap and through beam loading effect can be neglected. (a) find the value of deflected voltage  $V_0$  (b) find the dc necessary to give microwave gap of voltage of 200V (c) calculate the electronic frequency.

Solution

(a)

$$\frac{V_0}{(V_R - V_0)^2} = \frac{1}{8} \frac{1}{\omega^2 L^2} \frac{e}{m} \left[ 2n\pi - \frac{\pi}{2} \right]^2$$

$$\frac{1}{8} \times \frac{(1.759 \times 10^{11}) (2\pi/2) - \pi/2)^2}{(2\pi \times 8 \times 10^9)^2 (10^{-3})^2}$$

$$V_0 = 0.023$$

$$(V_R - V_0)^2 = 600 \times 0.023 = 11.508 \quad V_R - V_0 = 11.5$$

$$V_R = 3.39 + 500 = 503.39 \text{ Volts}$$

(b) Assuming  $B_0 = 1$

$$V_i = R_{sh} \cdot I_d = 2I_d J_1(x') R_{sh}$$

$$I_d = \frac{V_i}{2J_1(x') R_{sh}} = \frac{200}{2 \times 0.582 \times 20 \times 10^3} = 8.59 \times 10^{-3} A$$

$$(c) \text{ efficiency } \eta = \frac{2x' J_1(x')}{2n\pi - \pi/2}$$

$$x' = \frac{B_i V_i \phi}{2V_0}$$

$$x'_0 = \omega T'_0 = \frac{\omega g \cdot m L V_b}{e(V_R - V_0)} \Rightarrow \frac{2\pi \times 8 \times 10^9 \times 2 \times 10^{-3} \times 0.593 \times 10^6 \sqrt{500}}{1.579 \times 10^{11} \times [503 - (-500)]}$$

$$x'_0 = 7.556$$

for  $B_i = 1$

$$x' = \frac{200 \times 7.556}{2 \times 500} = 1.51$$

$$x' = 1.51 \text{ from graph, } x' J_1(x') = 0.84$$

$$\eta = \frac{2 \times 0.84}{2\pi(\alpha) - \pi/2} = 15.98\%$$

Example 7:- A reflex klystron operates at the peak of  $n = 100$  3/4 mode. The dc power input is 40 mW and ratio of  $V_1$  over  $V_0$  is 0.278 (a) determine the efficiency of reflex klystron (b) find the total power output in mW (c) If 20% of the power delivered by the electron beam is dissipated in the cavity walls find the power delivered to the load

$$(a) \eta = \frac{2x' J_1(x')}{2\pi + \pi/2} \quad n=1 \quad x' = 0.278 \times \frac{3\pi}{2} \times \frac{1}{2} = 0.655$$

$$(b) P_{out} = \frac{8.91}{100} \times 40 \times 10^{-3} = 3.564 \text{ mW}$$

$$(c) \text{Power delivered to load} = 3.564 \times \frac{80}{100} = 2.85 \text{ mW}$$

Example 8:- A normal circular magnetron has the following parameters  
Inner Radius  $R_a = 0.15 \text{ m}$  outer radius  $R_o = 0.45 \text{ m}$  magnetic flux density  $B_0 = 1.8 \text{ mwb/m}^2$  (a) determine the hull-cut-off voltage (b) determine the cut-off magnetic flux density if the beam voltage  $V_0$  as 6000V (c) determine the cyclotron frequency in GHz.

$$(a) \text{cut-off voltage } V_0 = \frac{eB_0^2 b^2}{8} m \left[ 1 - \frac{a^2}{b^2} \right]^2$$

$$= \frac{1.759 \times 10^{11}}{8} (1.8 \times 10^3)^2 (0.45)^2 \left[ 1 - \left( \frac{0.15}{0.45} \right)^2 \right]^2$$

$$= 50.666 \text{ kV}$$

$$(b) B_c = \frac{\sqrt{8V_0 m/e}}{b \left[ 1 - \frac{a^2}{b^2} \right]} = \sqrt{\frac{8 \times 6000}{(1.759 \times 10^{11})^2} \times \frac{1}{45 \left[ 1 - \left( \frac{0.15}{0.45} \right)^2 \right]}}$$

$$= 130.595 \text{ m Wb/m}^2$$

$$W_c = \frac{eB_0}{m} \quad \therefore f_c = \frac{1.759 \times 10^{11} \times 1.8 \times 10^3}{2\pi} \quad \boxed{f_c = 0.336 \text{ Hz}}$$

Example 9 A helical TWT has diameter as 2mm with 50 turns per cm.

(a) calculate axial phase velocity the anode voltage at which the TWT can be operated for useful gain.

$$(a) V_p = \text{velocity of light} \times \frac{\text{pitch}}{\text{circumference}}$$

$$\text{pitch} = \frac{1}{50 \text{ cm}} = 0.02 \text{ cm} = 2 \times 10^{-4} \text{ m}$$

$$\text{circumference} = \pi \times D = \pi \times 2 \times 10^{-3} \text{ m} = 6.284 \times 10^{-3} \text{ m}$$

$$V_p = 3 \times 10^8 \times 2 \times \frac{10^{-4}}{6.284 \times 10^3}$$

$$(b) eV_0 = \frac{1}{2} m V_p^2$$

$$V_0 = \frac{1}{2} \frac{m}{e} V_p^2 = \frac{1}{2} \times 9.1 \times \frac{10^{-31}}{1.6 \times 10^{19}} \times (0.9548 \times 10^7)^2$$

$$V_0 = 25.92 \text{ kV}$$

Example: 10 A two klystron amplifier has the following parameters

Beam voltage  $V_0 = 900 \text{ V}$  Beam current  $I_0 = 30 \text{ mA}$  frequency  $f = 8 \text{ GHz}$  Gap spacing between centres of cavities  $L = 4 \text{ cm}$  effective shunt impedance  $R_{sh} = 40 \text{ k}\Omega$  determine (a) the electron velocity (b) the d.c. electron transit time (c) the input voltage for maximum output voltage (d) the input gain in decibels.

$$(a) V_0 = 0.593 \times 10^6 \sqrt{900} \\ = 17.79 \times 10^6 = 1.8 \times 10^7 \text{ m/s}$$

$$(b) \text{Transit time} = \frac{d}{V_0} = \frac{1 \times 10^{-3}}{1.8 \times 10^7} = 0.55 \times 10^{-10} \text{ s}$$

$$(c) \text{Gap transit angle } \theta_g = \omega \frac{d}{V_0} = 2\pi (8 \times 10^9) \frac{10^{-3}}{1.8 \times 10^7} = 2.8$$

Beam coupling eff coefficient

$$B_i = B_o = \frac{\sin(2.8/2)}{2.8/2} = 0.704$$

$$\text{dc transit angle } \theta_0 = \frac{\omega L}{V_0} = 2\pi (8 \times 10^9) \frac{4 \times 10^{-2}}{1.8 \times 10^7} = 111.64$$

For maximum output voltage,  $V_0$

$$J_1(x) = 0.582, x = 1.841$$

$$V_{1\max} = \frac{2(900)(1.841)}{0.704 \times 111.64} = 48.16 \text{ V}$$

$$(d) Av = \frac{(0.704)^2 (111.64) (0.582) (40 \times 10^3)}{30 \times 10^3 \times 1.841} = 23.38$$

Example: 11 A four cavity klystron amplifier has the following parameters.

Beam voltage  $V_0 = 80 \text{ kV}$  Beam current  $I_0 = 2 \text{ A}$  operating frequency  $f = 9 \text{ GHz}$

dc charge density  $P_0 = 10^6 \text{ c/m}^3$

RF charge density  $P = 10^8 \text{ c/m}^3$  velocity

Perturbation  $v = 10^5 \text{ m/s}$ .

Determine (a) the dc electron velocity (b) the dc phase constant (c) the plasma frequency (d) the reduced plasma frequency for  $R = 0.5$  (e) the beam current density (f) the instantaneous beam current density.

(a) The dc electron velocity  $v_0 = 0.593 \times 10^6 \sqrt{20 \times 10^3} = 8.386 \times 10^7 \text{ m/s}$

(b) The d.c phase constant  $\beta_e = \frac{2\pi \times 9 \times 10^9}{8.386 \times 10^7} = 6.74 \times 10^2 \text{ rad/m.}$

(c) plasma frequency  $\omega_p = \sqrt{1.759 \times 10^{11} \times \frac{10^6}{8.854 \times 10^{-12}}} = 1.41 \times 10^8 \text{ rad/s}$

(d) Reduced plasma frequency

$$\omega_q = 0.5 \times 1.41 \times 10^8 = 0.705 \times 10^8 \text{ rad/s}$$

(e) d.c beam current density

$$J_0 = 10^6 \times 8.386 \times 10^7 = 83.86 \text{ A/m}^2$$

(f) Instantaneous beam current density

$$J = 10^8 \times 8.386 \times 10^7 = 10^6 \times 10^5$$

$$J = 0.7386 \text{ A/m}^2$$

Example 12 A reflex klystron is operated at 56 MHz with an anode voltage of 1000 V and cavity gap 2mm calculate the gap transit angle. find optimum length of the drift region Assume  $N = 1.3/4$ .  $V_R = -500 \text{ V}$ .

$$|V_R| = 6.74 \times 10^6 \text{ F/m} \sqrt{V_0} - V_0$$

$$500 = \frac{6.74 \times 10^6 \text{ F/m} \sqrt{V_0}}{N} - V_0$$

$$L = 2.463 \text{ mm (length of drift region)}$$

Also gap transit angle  $= \omega t g = \frac{\omega d}{v_0}$

$$d = 2 \times 10^{-3} \text{ m}, v_0 = 8.386 \times 10^7 \sqrt{V_0} = 18.75 \times 10^6 \text{ m/s}$$

$$\omega = 5 \times 10^9 \text{ rad/s}$$

$$\text{Transit angle, } \theta_g = \frac{2\pi \times 5 \times 10^9 \times 2 \times 10^{-3}}{18.75 \times 10^6}$$

$$\theta_g = 3.351 \text{ radians}$$

Example:-13 A two cavity klystron is operated at 10 GHz with  $V_0 = 1200$  V,  $I_0 = 30mA$ ,  $d = 1mm$ ,  $L = 4cm$  and  $R_{sh} = 40k\Omega$ . Neglecting beam loading calculate (a) input RF voltage  $V_I$  for a maximum output voltage (b) voltage gain and (c) efficiency.

The bunching parameter  $\chi$  is given by

$$\chi = \frac{V_I}{2V_0} \theta_0$$

where  $\theta_0$  = transit angle without RF voltage.

$$\theta_0 = \frac{\omega L}{v_0}$$

$v_0$  = velocity of reference electron

$$v_0 = 0.593 \times 10^6 \sqrt{V_0} = 20.54 \times 10^6 \text{ m/s}$$

$$\theta_0 = \frac{2\pi \times 10 \times 10^9 \times 4 \times 10^2}{20.54 \times 10^6} = 122.347 \text{ rad}$$

$$V_I = \frac{2\chi \cdot V_0}{\theta_0}$$

Now for maximum output power (and hence maximum output voltage)

$$\chi = 1.84$$

$$(V_I)_{max} = \frac{2 \times 1.84 \times 1200}{122.347} = 36.09 \text{ V}$$

If beam coupling coefficient is considered

$$V_I = \frac{2\chi \cdot V_0}{\beta_i \theta_0}$$

$$\beta_i = \frac{\sin \theta_g/2}{\theta_g/2}$$

$$\theta_g = \text{average gap transit angle} = \frac{\omega d}{v_0}$$

$$\theta_g = \frac{122.347}{4 \times 10^2} \times 10^{-3} = 3.05 \text{ and } \frac{V_0}{v_0}$$

$$\beta_i = \frac{\sin 1.5293}{1.5293} = 0.653$$

$$(V_I)_{max} = \frac{36.09}{0.653} \text{ and } 55.863 \text{ V.}$$

(b) Voltage gain  $A_V$  is given by

$$A_V = V_2/V_1.$$

where  $V_2 = B_0 I_0 R_{sh}$

$B_0$  = output cavity coupling coefficient =  $\beta_i$

$$I_0 = 2 I_0 J_1(X)$$

for  $X = 1.84 \quad J_1(X) = 0.58$

$$I_0 = 2 \times 30 \times 10^{-3} \times 0.58$$

$$V_2 = 0.653 \times 2 \times 30 \times 10^{-3} \times 0.58 \times 40 \times 10^3$$

$$V_2 = 909.49 V$$

$$AV = \frac{V_2/V_1}{1} = \frac{909.49}{55.268} = 16.45$$

$$AV = 24.33 \text{ dB}$$

(c) maximum efficiency is given by

$$\eta = 0.58 \times V_2 / V_0$$

$$\eta = \frac{0.58 \times 909.49}{1200}$$

$$\eta = 43.95\%$$

Example:-14 An X-band cylindrical magnetron has  $V_0 = 30 \text{ kV}$ ,  $I_0 = 80 \text{ Am}$ ,  $B_0 = 0.01 \text{ wb/cm}^2$ ,  $a = 4 \text{ cm}$ ,  $b = 8 \text{ cm}$  calculate (a) cyclotron angular frequency  
(b) cut-off voltage and (c) cut-off magnetic flux density

Sol (a) cyclotron angular frequency is given by

$$\omega = \frac{e B_0}{m}$$

$$\omega = \frac{1.6 \times 10^{-19} \times 0.01}{9.1 \times 10^{-31}} = 1.758 \times 10^9 \text{ rad/s}$$

(b) Hull-cut-off voltage is given by

$$V_{HC} = \frac{e B_0^2 b^2}{8m} \left[ 1 - \frac{a^2}{b^2} \right]^2$$

$$V_{HC} = \frac{1}{8} \times 1.758 \times 10^9 \times (0.01)^2 \times (8 \times 10^{-3})^2 \times \left[ 1 - \frac{4^2}{8^2} \right]^2$$

$$V_{HC} = 7.9155 \text{ kV}$$

(c) cut-off magnetic flux density given by

$$B_C = \frac{(8 V_0 m/e)^{1/2}}{b \left[ 1 - a^2/b^2 \right]}$$

$$B_C = \left[ \frac{8 \times 30 \times 10^3}{1.759 \times 10^{11}} \right]^{1/2} \times \frac{1}{8 \times 10^2 \left[ 1 - \frac{4^2}{8^2} \right]}$$

$$B_C = \frac{1}{0.06} \times 0.001168$$

$$B_C = 19.468 \text{ m wb/m}^2$$

Example 15: A reflex klystron operates at the peak mode of  $n=2$  with  $V_0 = 280 \text{ V}$ ,  $I_0 = 22 \text{ mA}$  and signal voltage  $V_1 = 30 \text{ V}$  determine (a) the input voltage (b) the output power (c) the efficiency

$$(a) P_{dc} (\text{input power}) = V_0 I_0 = 280 \times 22 \times 10^{-3}$$

$$(b) P_{ac} (\text{output power}) = \frac{2V_0 I_0 \times J_1(x)}{2n\pi - \pi/2}$$

$$= \frac{2 \times 6.16 \times 1.25}{2 \times 2 \times \pi - \pi/2} = \frac{15.4}{7\pi} \times 2 = 1.4 \text{ watts.}$$

$$(c) \eta = \frac{P_{ac}}{P_{dc}} \times 100 = \frac{1.40}{0.16} \times 100$$

$$\eta = 87.5\%$$

Example 16: A reflex klystron operates at  $8 \text{ GHz}$  at peak of  $n=2$  mode with  $V_0 = 300 \text{ V}$ ,  $R_{sh} = 20 \text{ k}\Omega$  and  $L = 1 \text{ mm}$  and if the gap transit time and beam loading are neglected. find the (a) repeller voltage (b) beam current necessary to obtain an RF gap voltage of  $200 \text{ V}$ .

(a) Repeller voltage is given by  $V_R$

$$\frac{V_0}{(V_R - V_0)^2} = \frac{1}{8} \frac{e}{\omega^2 L^2 m} \left[ 2n\pi - \pi/2 \right]^2$$

$$\frac{1}{8} \times \frac{1.759 \times 10^{11} \times [2\pi \times 2 - \pi/2]^2}{(2\pi \times 8 \times 10^9)^2 \times (10^{-3})^2}$$

$$\frac{V_0}{(V_R - V_0)^2} = 0.00105$$

$$(V_R - V_0)^2 = \frac{300}{0.00105} = 285 \times 1.34 \times 10^3$$

$$V_R - V_0 = 533.98 \text{ V}$$

$$V_R = 533.98 + V_0 = 833.98 \text{ V}$$

(b) Assuming output coupling coefficient  $B_0 = 1$ .

$$V_i = I_a \cdot R_{sh} = 2I_0 J_1(x') R_{sh}$$

$$\begin{aligned} I_0 &= \frac{V_i}{2J_1(x') R_{sh}} \\ &= \frac{260}{2 \times 0.582 \times 20 \times 10^3} \\ I_0 &= 8.59 \text{ mA} \end{aligned}$$

## Microwave Solid State Devices:-

### Introduction:-

As we have been seen in the previous chapters of microwave tubes, the amplification, oscillations, switching, limiting or frequency multiplication basically employed velocity modulation theory. However in the recent past there has taken place a tremendous research activity for development of better, low noise, high frequency, greater bandwidth lesser switching time and other improvements in the performance characteristics for achieving the above functions. In this endeavor, several semiconductor microwave devices have been developed which include three terminal devices such as bipolar and field effect transistors and two terminal devices such as transferred electron devices (IMPATT, TRAPATT, BARITT parametric devices), avalanche transit time devices (Gunn diodes, LSA devices), tunnel diode, varactors, quantum electronic devices such as MASERS, semiconductors lasers and ~~infrared~~ devices.

All the above mentioned solid state devices employ negative resistance characteristics rather than velocity modulation for their operation. These devices have been commonly utilized for several applications that include modern communication systems, radars, navigation, medical and biological equipment and other industrial electronic products.

## Classification, Applications.

### Applications:-

GaAs MESFETs due to their excellent performance characteristics have found a number of microwave applications.

1. As front end low noise amplifiers of microwave receivers in both radar and communications
2. As power amplifiers for output stage of microwave links
3. As driver amplifiers for high power transmitters
4. As output amplifiers in narrow band troposcatter links as in broad band generators
5. As power oscillators
6. Dual gate MESFET as can be used for harmonic frequency multiplication upto K band

## Classifications of solid state microwave devices

Solid state microwave devices can also be classified

1. Based on their electrical behaviour
2. Based on their construction

Based on electrical behaviour we have,

- (a) non-linear resistance type: eg varistors (variable resistance)
- (b) Non-linear resistance type: eg varactors (variable reactors)
- (c) Negative resistance type: eg tunnel diode, Impatt diode, Gunn diode
- (d) controllable impedance type: eg p/n diode

Based on construction we have,

- (a) point contact diodes
- (b) schotthy barrier diodes
- (c) metal oxide semiconductor devices (MOS)
- (d) metal insulation devices

## TED's Introduction:

### Transferred Electron Devices (TED's)

As we have seen before, the common characteristics of all active two terminal devices (solid-state) in their negative resistance. The real part of their impedance is negative over a range of frequencies.

In a positive resistance the current through the resistance is positive and a power of  $I^2R$  is dissipated in the resistors. In a negative resistance. In other words positive resistance absorb power (passive devices) and negative resistances generate power (active devices).

TED's are bulk devices having no junction, or gate as compared to microwave transistors which operates with junction or gate. TED's are fabricated from compound semiconductors such as GaAs, InP (Indium Phosphate) CdTe (cadmium telluride) as against Ge and Si of transistors.

TED's operates with hot electrons whose energy is very much greater than the thermal energy. Transistor operates with warm energy electrons whose energy is not much greater than their thermal energy (0.026 eV at room temperature). Gunn diode is example for TED's.

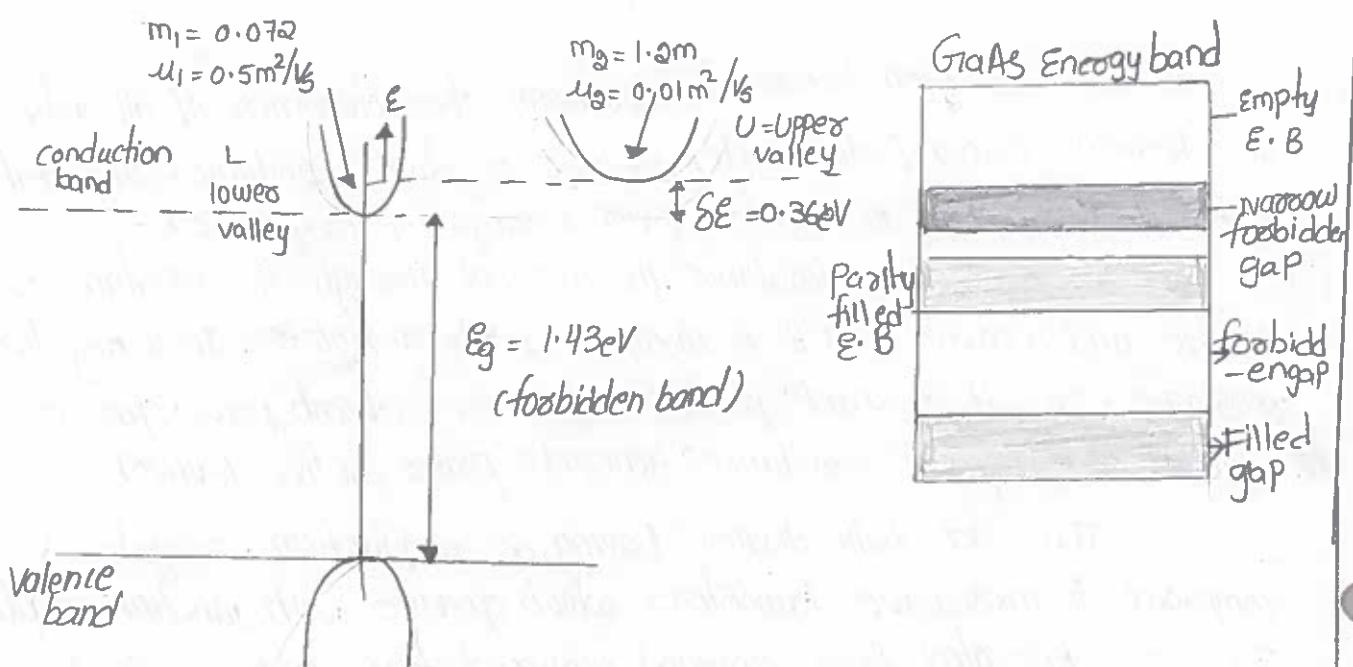
## Gunn-diode Principle, RWH Theory

Gunn Effect diodes are named after J.B. Gunn (1963), who discovered periodic fluctuations of current passing through the n-type GaAs specimen when the applied voltage exceeded a certain critical value (0-4 KV/cm<sup>2</sup>). Gunn effect can be explained on the basis of two valley theory of Ridley Watkins - Hilsum (RWH) theory or the transferred electron mechanism.

Basic mechanism involved the operation of bulk n-type GaAs devices is the transferred of electrons from lower conduction valley L-valley to upper subsidiary valley the V-valley.

The curvature of two valley in conduction band also called the subbands are different so that an electron in L-valley has smaller effective mass than one in V-valley.

The ratio of density of states in U-valley to that V-valley is about 60. O-valley have high density when compared with  $k=0$  location.



At low ( $0 \leq E \ll E_g$ ) electric field, conduction electrons are distributed in a manner determined by energy separation  $\Delta E$ , the lattice temperature  $T_0$  and the density of states. with typical values stated in figure, most of electrons at low electric field and low lattice temperature will occupy states in L-valley and carry ohmic current  $J = \sigma E$

with  $\sigma \approx p n_1 \mu_1 \approx e n_1 \mu_1$ , where  $n_1$  is the carrier concentration in L-valley and is assumed to equal to the total carrier concentration  $n_0$  and  $\mu_1$  is mobility in L-valley as applied field is increased electron gain energy from it and move upward in the U-valley inner valley transfer of electrons is good as there are many available states in the U-valley. the mobility decreased effective mass is increased thus decreasing current density  $J$ . There is certain threshold field approximately  $3.3 \text{ kV/cm}$  above which inner valley transfer also known as the population inversion or changes to L-valley lower to U-valley as the transfer electron effect take places.

$$J = \sigma E = \rho(n_1 + n_2) \bar{\mu} E = e n_0 \bar{\mu} E$$

where  $\bar{\mu} = \frac{n_1 \mu_1 + n_2 \mu_2}{n_0}$  = the average mobility of electrons.

the electrons in L-valley are transferred to U-valley and the current density will given

$$J = \sigma E \approx e n_2 \mu_2 E$$

where,  $n_g$  = carrier concentration  
 $n_i$  = mobility in U-valley.

### Characteristic, Applications

the v-I characteristics of pn junction diodes for voltage controlled bulk negative conductance GaAs

$J_m$  = maximum current density

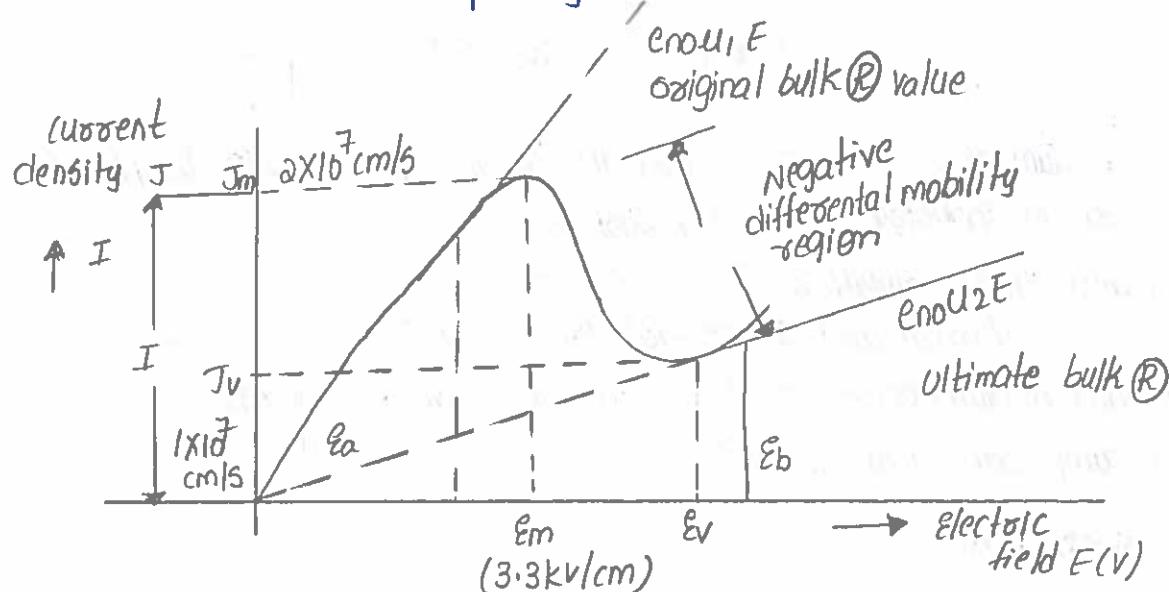
$J_v$  = valley current density

$E_m$  = maximum electric field required before the onset of negative conductance region

$E_a$  = maximum electric field for which  $J = \sigma E$  is valid

$E_b$  = electric field for which  $J = E n_2 u_2 E$  holds

$e_v$  = electric field corresponding to  $J_v$



$J-E$  characteristic of a Gunn diode

$$u_d = v/dE$$

$$u_n = \frac{dV_d}{dE}$$

$$u_u = V_d/E$$

$$V_d = fL$$

where,  $V_d$  = electron drift velocity

$f$  = frequency

$L$  = device length

$I$  = terminal current

$E \propto$  applied voltage  $V$

Hence these  $J-E$  characteristics represent the v-I characteristics of Gunn diode. the region of the characteristics between  $E_m$  and  $E_v$  where current density decreases with increasing field is one of negative differential resistivity (NDR)

differentiating  $J = \sigma E = e n_0 \bar{\mu} E$  w.r.t to  $E$  we get,

$$\frac{dI}{dE} = \sigma \left[ 1 + \frac{E}{\sigma} \frac{d\sigma}{dE} \right]$$

The condition for negative conductance (or resistance) is

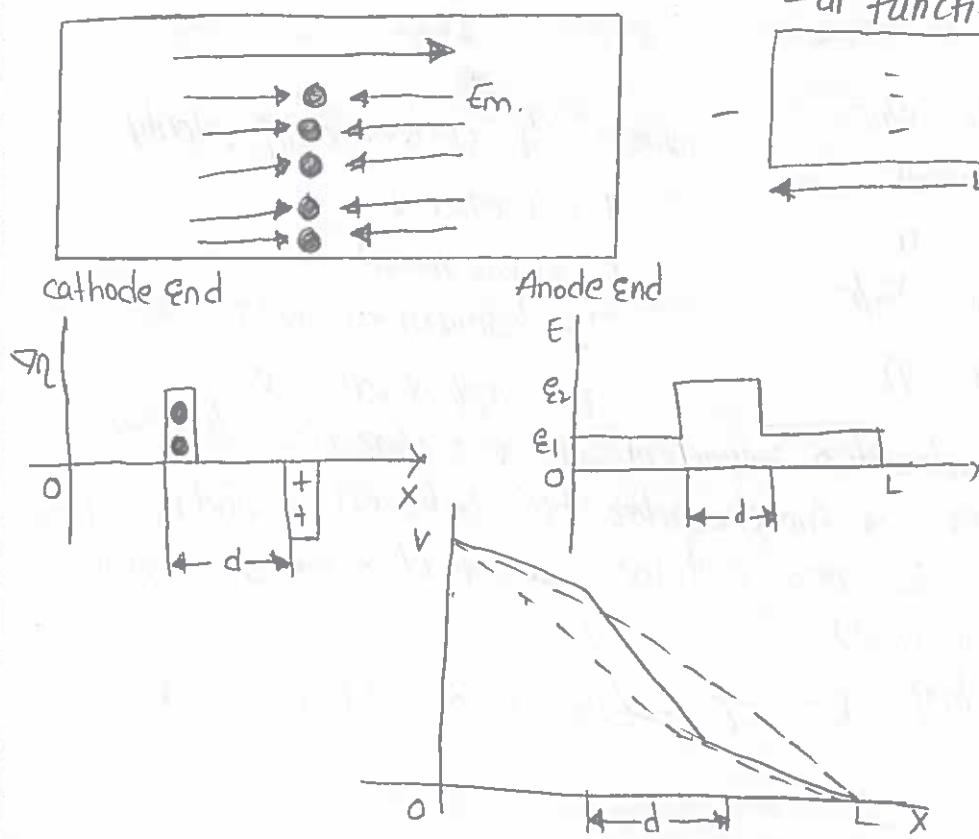
$$\frac{dI}{dE} < 0 \Leftrightarrow 1 + \frac{E}{\sigma} \frac{d\sigma}{dE} < 0$$

Here  $d\sigma/dE$  satisfies the above condition i.e., if differential conductivity is negative then slope of the V-I characteristics will be negative and conductance to the external circuit. It is to be noted here that this inner valley transfer must after realistic field levels. The threshold field  $E_m$  should not raise the temperature so high as to cause significant generation of electron from valence band by impact ionization. Thus  $\delta E$  should be less than  $E_0$ , in the case of n-type GaAs ( $\delta = 0.36 \text{ eV}$ ,  $E_0 = 1.43 \text{ eV}$ )

### Applications of Gunn diode

1. In radar transmitters (Police Radar, CW Doppler Radar)
2. Pulsed Gunn diode oscillators used in transponders for air traffic (ATC) control and in industry telemetry systems.
3. Broadband linear amplifiers (replacing TWT's).
4. Fast combinational and sequential logic circuits.
5. Low and medium power oscillator in microwave receivers.
6. As pump sources in laser pump.

### Modes of operations



layer of excess electron due to thermal function (noise) in carrier density

fig:- Dipole domain formation

#### 4. Limited space charge accumulation mode ( $f_L > 2 \times 10^7$ cm/sec)

this is the most important mode operation of Gunn oscillator. This mode gives high power with high efficiency. domain is not allowed to form at all. Efficiency  $\eta$  20%. 16 to 23% compared to Gunn mode. operating frequency 0.5 - 50 times more than Gunn mode. It can be used up to 100 GHz. High Q resonator needed LSA. this device is easily destroyed if domain is formed.

#### Gunn oscillation modes

A Gunn diode oscillator circuit normally consists of a resonant cavity, a circuit for biasing the diode and a mechanism to couple RF power to the diode and a mechanism to couple RF power from cavity to external circuit / load.

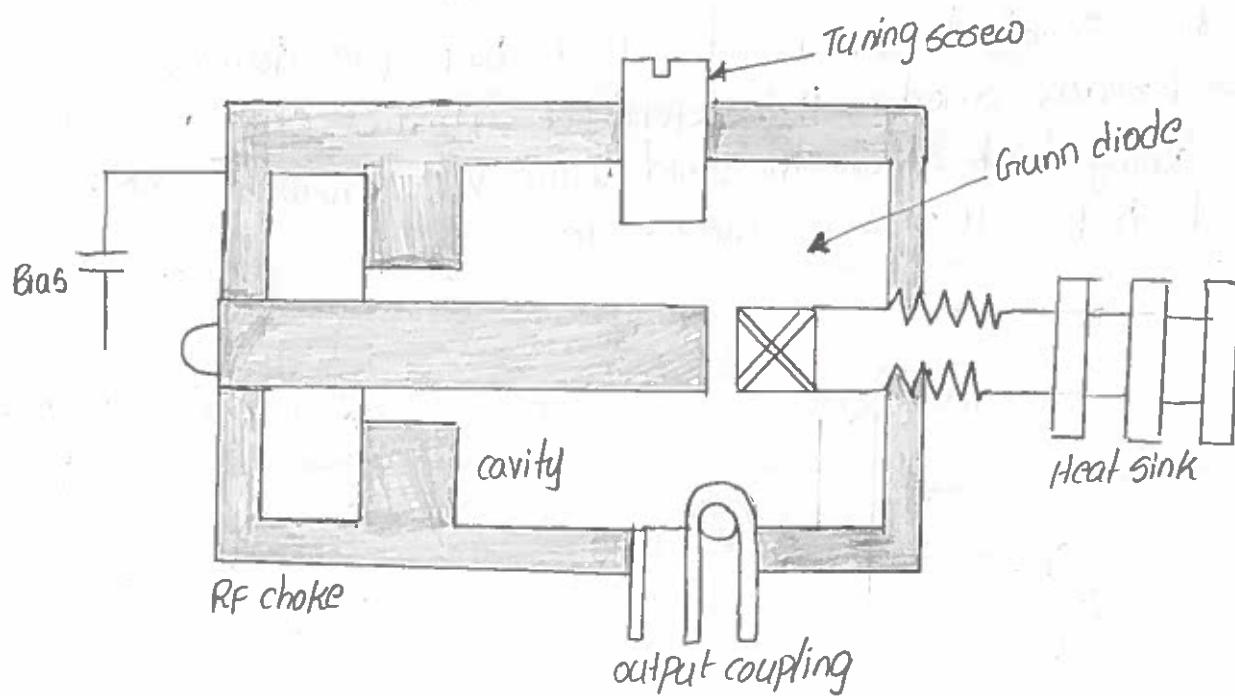


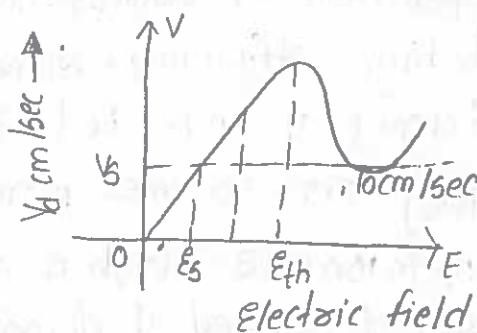
fig:- Gunn oscillator using co-axial cavity

The circuit using coaxial cavity has Gunn diode mounted at one end of the cavity. The output is taken using an inductively or capacitively probe coupled probe.

The circuit using waveguide cavity is more popular consisting of a simple waveguide section separated from output waveguide by an iris.

### 1. Transit Time domain mode ( $f_L = 10^7 \text{ cm/sec}$ )

this is also called Gunn diode  $f_L = 10^7 \text{ cm/sec}$  when  $\gamma_0 = \gamma_t$  high field domain is stable.  $\gamma_0 = \gamma_t$  period oscillation = transit time.



efficiency is below 10%.  $V_d$  depends on bias voltage.  $V_d$  = drift velocity the operating frequency is less than 30 GHz.

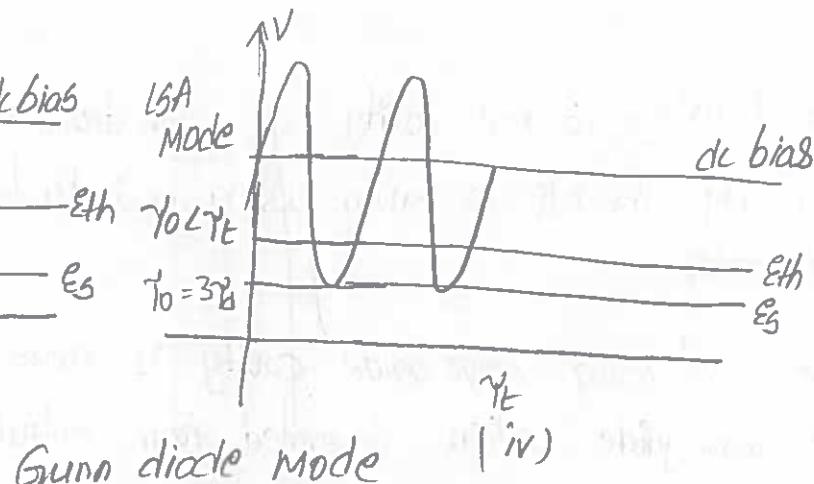
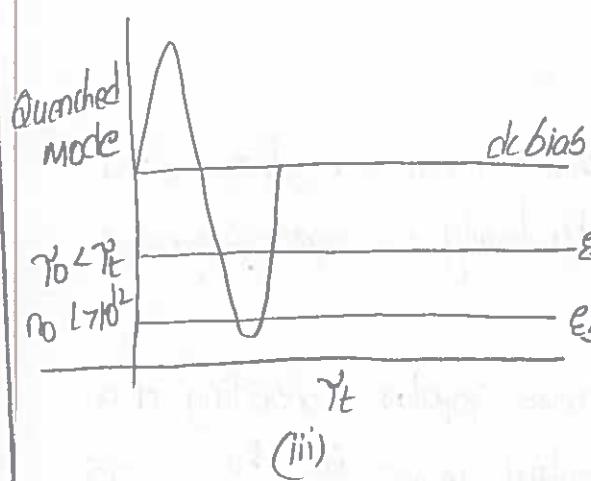
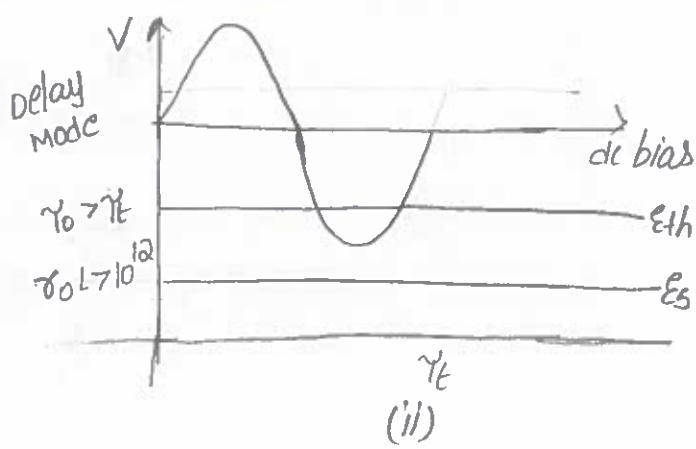
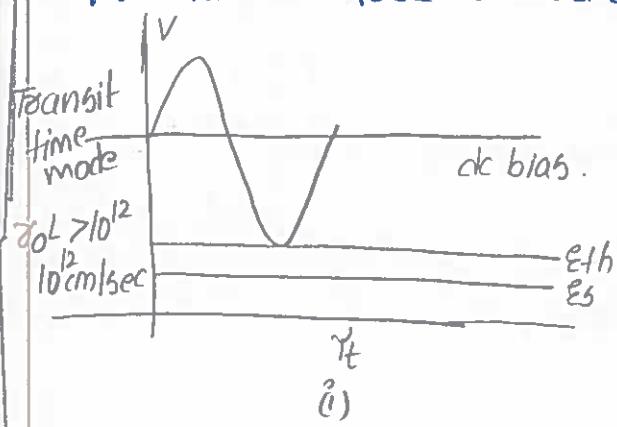
### 2. Delayed domain mode ( $10^6 \text{ cm/sec} < f_L \leq 10^7 \text{ cm/sec}$ )

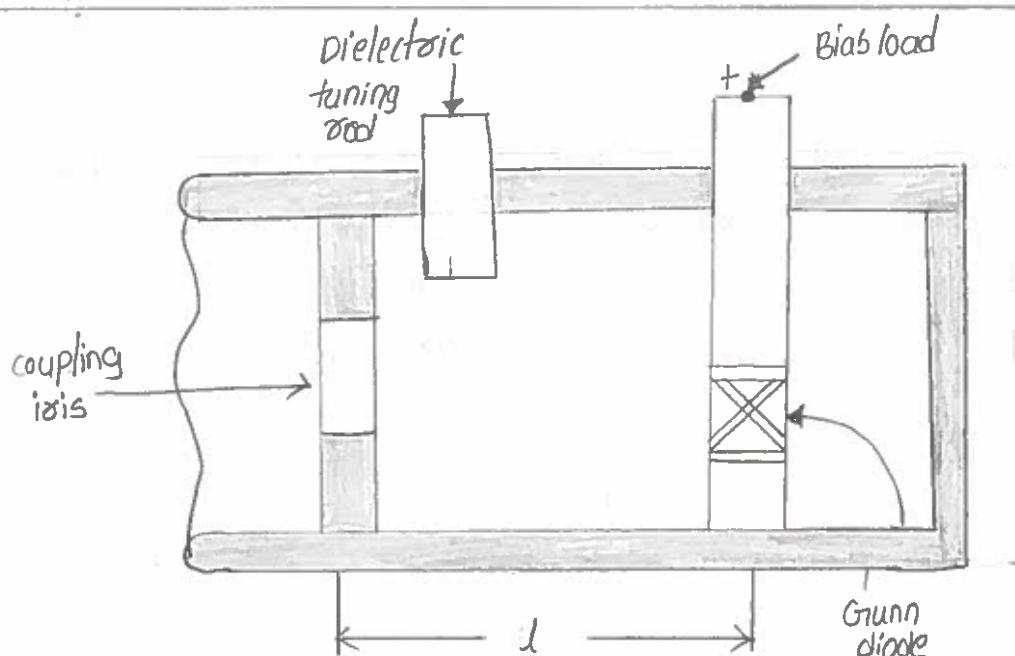
Transit time is chosen so that domain is collected while  $E < E_{th}$  a new domain cannot form until field rises again above threshold.  $\gamma_0 > \gamma_t$

$\eta$  of 20% approximately operating frequency to be equal to Gunn diode mode

### 3. Quenched domain mode ( $f_L > 2 \times 10^7 \text{ cm/sec}$ )

In this  $\epsilon_s$  during the negative field half cycle domain collapses before it reaches anode. This depends of external ckt. when bias field comes back above threshold value  $V_{th}$  a new domain is quenched before it reaches the anode.





Gunn oscillator circuit using waveguide

The rectangular cavity operates in the TE<sub>01</sub> mode. The diode post act as large inductive susceptance and the iōis is also inductive. Hence this resonant frequency is lower than that for which length  $l$  is  $\lambda_g/2$ . The dielectric tuning load is used to tune the frequency mechanically. Sapphia dielectric rod is commonly employed.

### Principle of operation of IMPATT diode

Any device which exhibits negative resistance for dc will also exhibit it for ac i.e. if ac voltage is applied current will rise when voltage falls at ac rate. Hence negative resistance can also be defined as the property of a device the current through 180° out of phase with the voltage across it. Negative resistance exhibited by IMPATT diode i.e. if we show voltage & current have 180° phase difference.

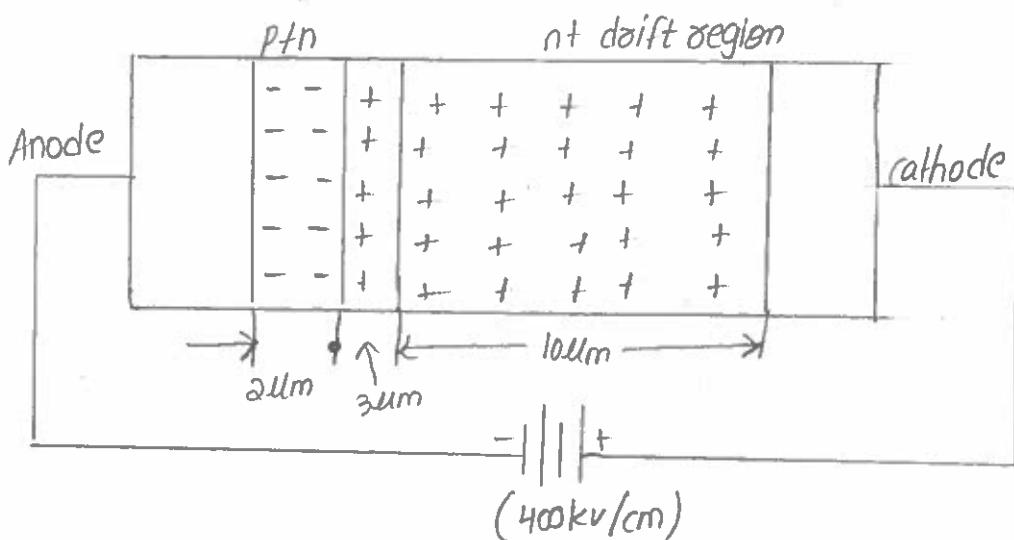
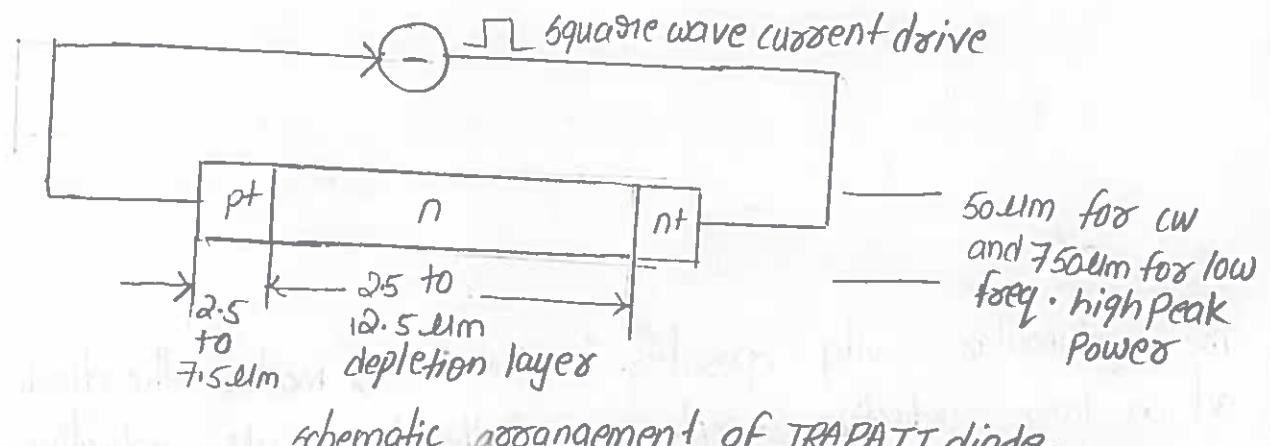


fig:- IMPATT diode schematic

## TRAPATT Diode

It is derived from the IMPATT diode and is closely related to it. It is high efficiency microwave generator capable of operating from several hundred MHz to several GHz. The basic operation of the oscillator is a semiconductor junction diode reverse biased to current densities well in excess of those encountered in normal Avalanche operation.



schematic arrangement of TRAPATT diode.

### operation

A high field avalanche zone propagates through the diode and fills the depletion region with a dense plasma of electrons & holes that becomes trapped in low field region behind the zone.

AB shows charging, BC shows plasma formation  
DF shows plasma extraction EF shows residual extraction FG shows charging.

The avalanche zone velocity  $v_2$  is given by

$$v_2 = \frac{dx}{dt} = \frac{J}{qN_A}$$

$J$  = current density  
 $q$  = electron charge  $1.6 \times 10^{-19}$   
 $N_A$  = doping concentration.

The avalanche zone will quickly sweep across most of diode, and the transit time of carrier is

$$\tau_s = \frac{L}{v_s}$$

$v_s$  = saturated carrier drift velocity  
 $L$  = length of the specimen.