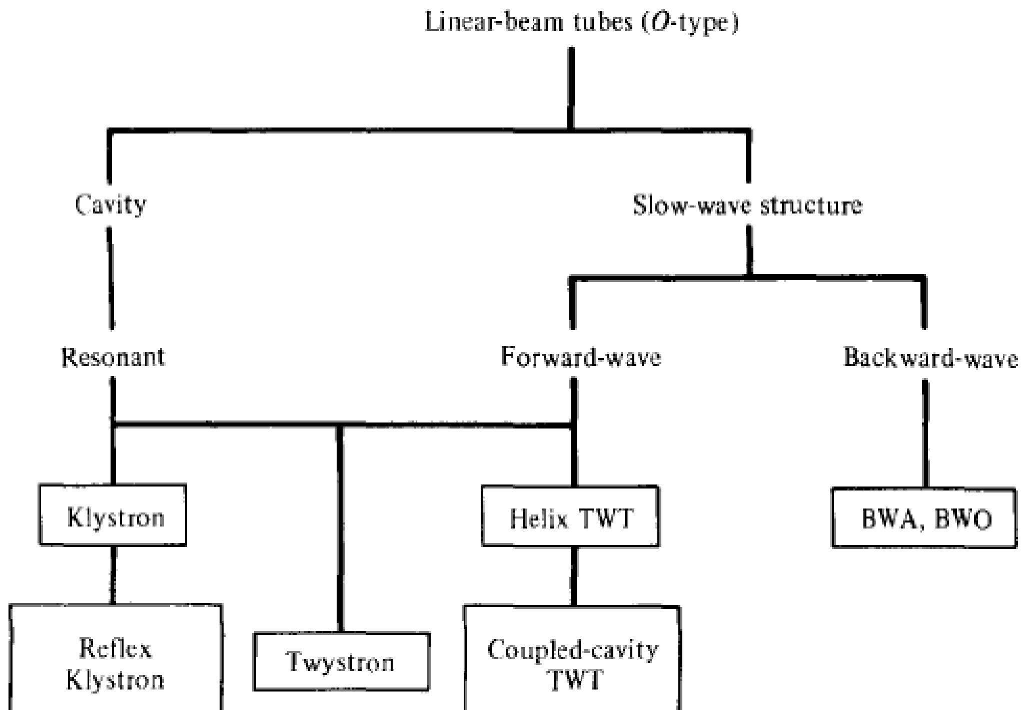
UNIT IV MICROWAVE TUBES AND MEASUREMENTS

Microwave Linear-Beam Tubes (0 Type)

- *O* -type tubes derive their name from the French ***TPO (tubes a propagation desondes)*** or from the word ***original*** (meaning the original type of tube).



Microwave Tubes

- In these tubes electrons receive potential energy from the dc beam voltage before they arrive in the microwave interaction region, and this energy is converted into their kinetic energy.
- In the microwave interaction region the electrons are either accelerated or decelerated by the microwave field and then bunched as they drift down the tube.
- The bunched electrons, in turn, induce current in the output structure. The electrons then give up their kinetic energy to the microwave fields and are collected by the collector

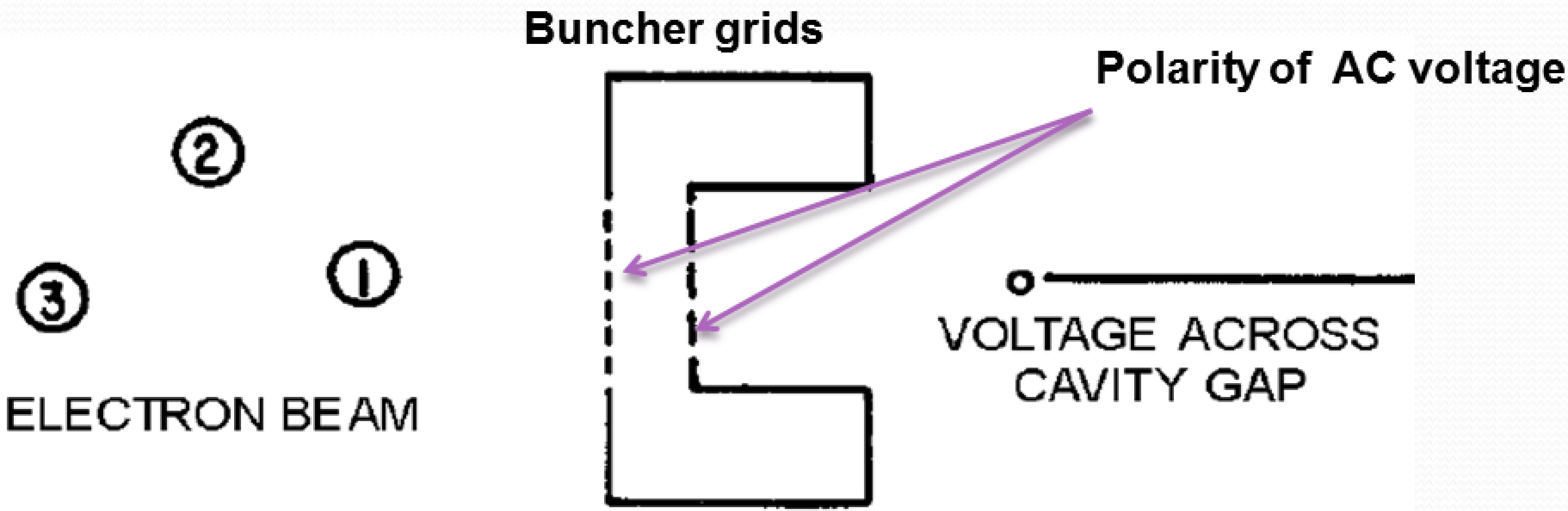
High Frequency Limitations

- Conventional vacuum tubes (electronic vacuum tubes)such as triodes, tetrodes, and pentodes are less useful signal sources at frequencies above 1 GHz because of,
    - Lead-inductance
    - Inter electrode -capacitance
    - Transit time
    - Gain-bandwidth product limitations

Velocity modulation of electrons

- The variation in electron velocity in the drift space is known as *velocity modulation.*
- Velocity modulation is defined as that variation in the velocity of a beam of electrons caused by the alternate speeding up and slowing down of the electrons in the beam. This variation is usually caused by a voltage signal applied between the grids through which the beam must pass.

Velocity modulation of electrons



Buncher cavity action. BUNCHER CAVITY.

Reentrant Cavities

- Reentrant cavity is one in which the metallic boundaries extend into the interior of the cavity.

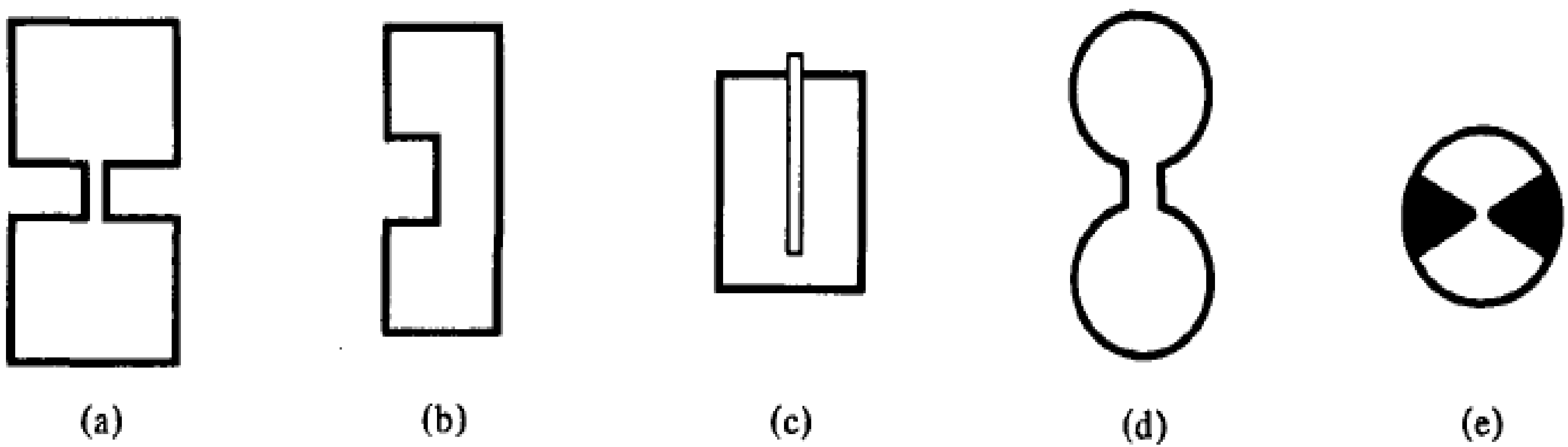


Figure 9-2-3 Reentrant cavities. (a) Coaxial cavity. (b) Radial cavity. (c) Tunable cavity. (d) Toroidal cavity. (c) Butterfly cavity.

KLYSTRON

Klystron is a vacuum tube that can be used either as a generator or as an amplifier of power, at microwave frequencies.

Two basic configurations of klystron tubes are,

- Two (Multi) cavity klystron – low power microwave amplifier
- Reflex Klystron –low power microwave oscillator

Two cavity Klystron

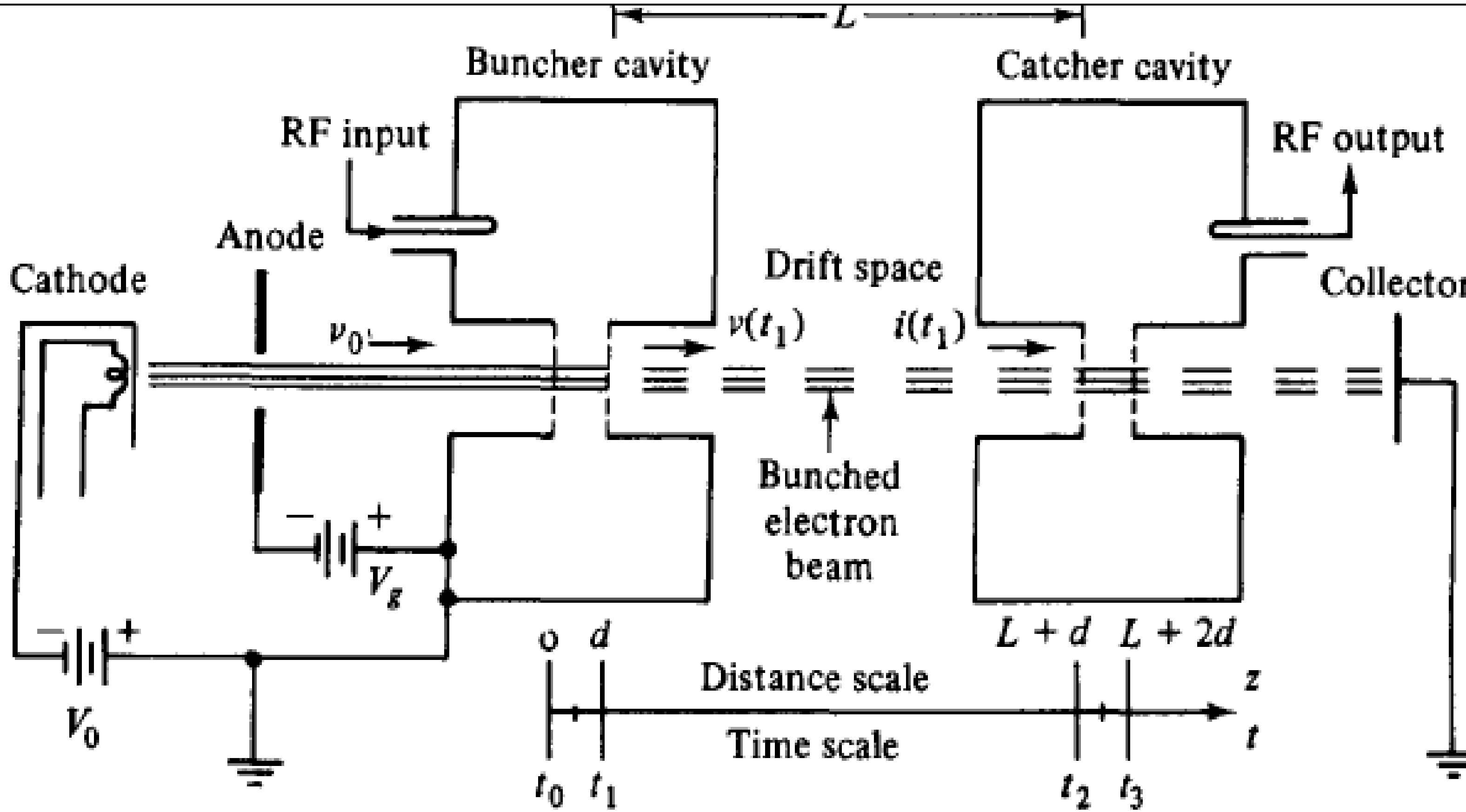
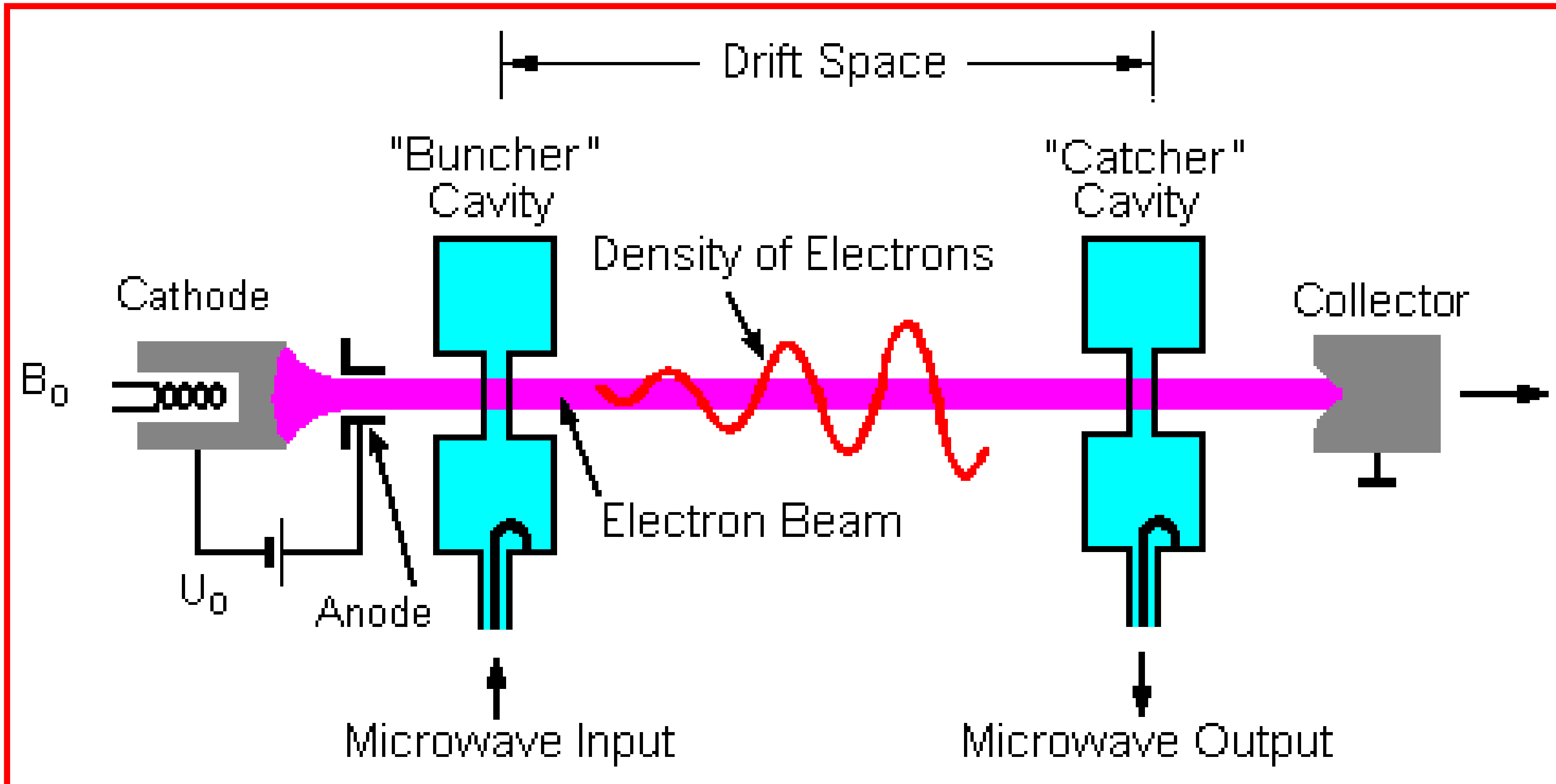
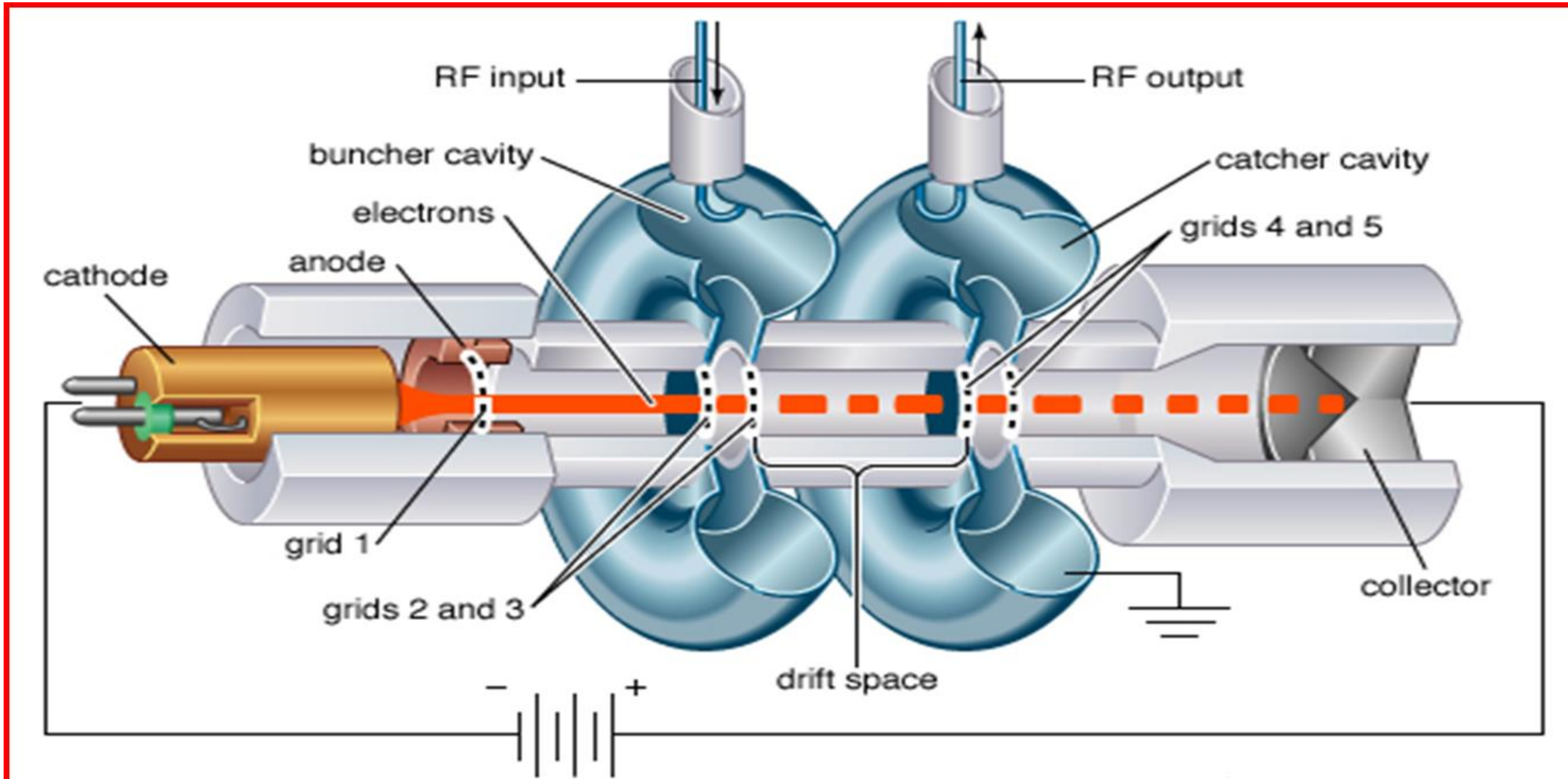


Figure 9-2-2 Two-cavity klystron amplifier.

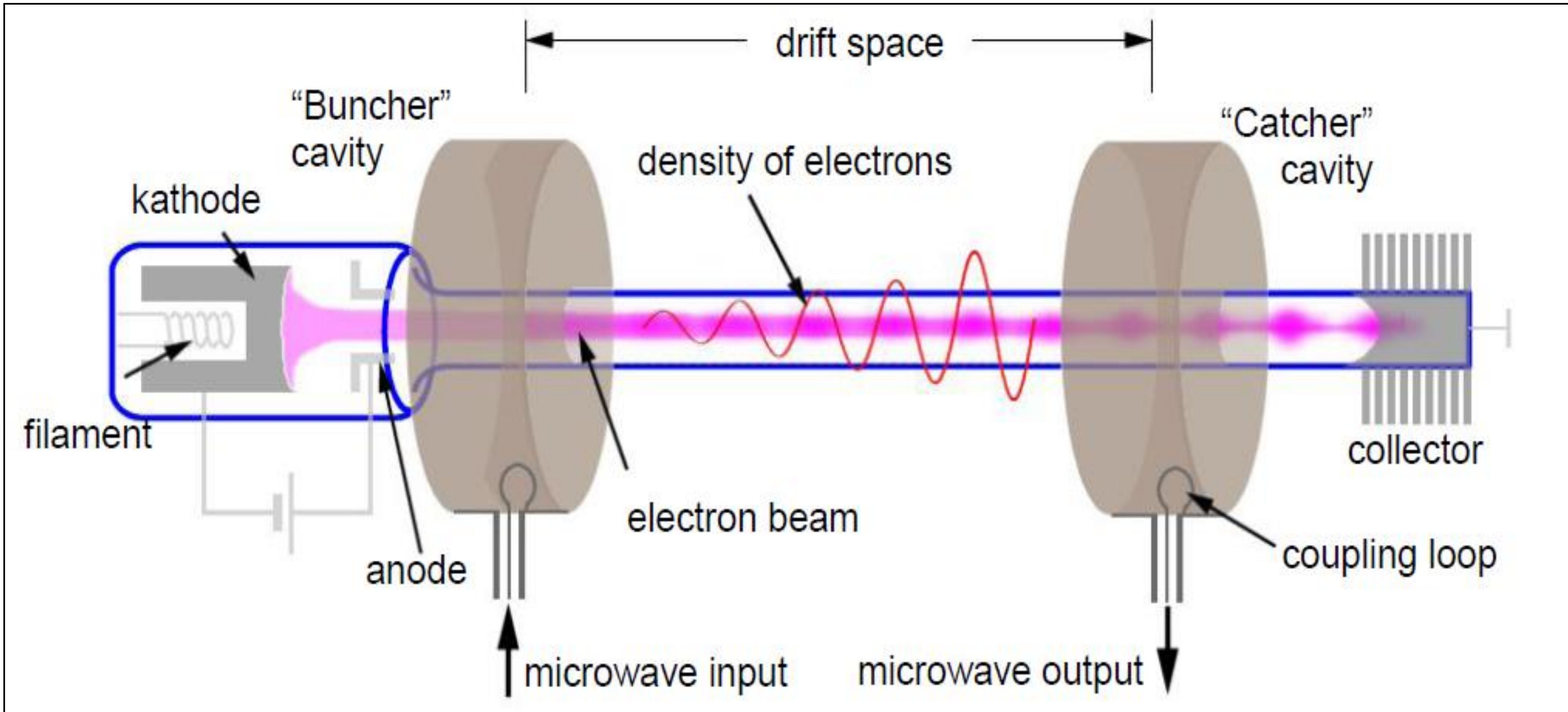
Two cavity Klystron



Two cavity Klystron



Two cavity Klystron



Two cavity Klystron

Buncher cavity

The direction of the field changes with the frequency of the “buncher” cavity. These changes alternately accelerate and decelerate the electrons of the beam passing through the grids of the buncher cavity

Catcher Cavity

The function of the “catcher” cavity is to absorb energy from the electron beam. The “catcher” grids are placed along the beam at a point where the bunches are fully formed. The location is determined by the transit time of the bunches at the natural resonant frequency of the cavities

Two cavity Klystron

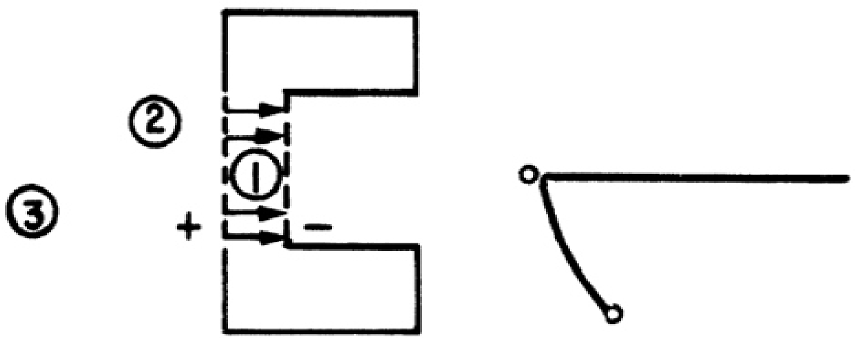
Drift Space

The area beyond the cavities is called the "drift space". The electrons form bunches in this area when the accelerated electrons overtake the decelerated electrons

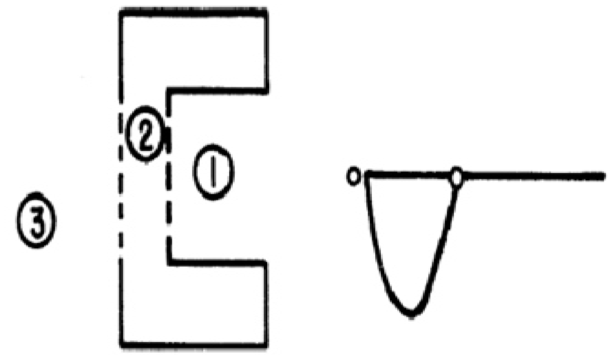
- The resonant frequency of the catcher cavity is the same as the buncher cavity

- The air-cooled collector collect the energy of the electron beam and change it into heat and X radiation

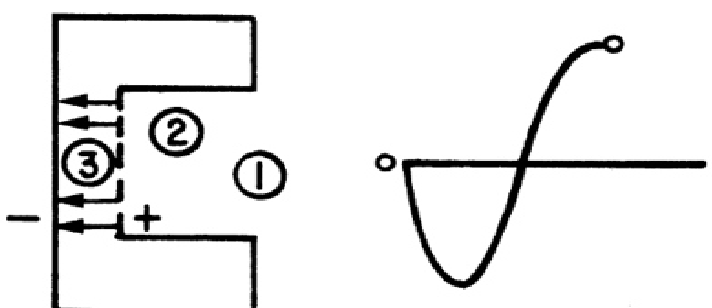
Electron beam via Buncher Cavity



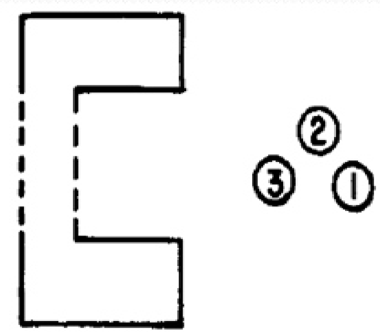
Buncher cavity action. ELECTRON #1 DECELERATED.



Buncher cavity action. ELECTRON #2 VELOCITY UNCHANGED.

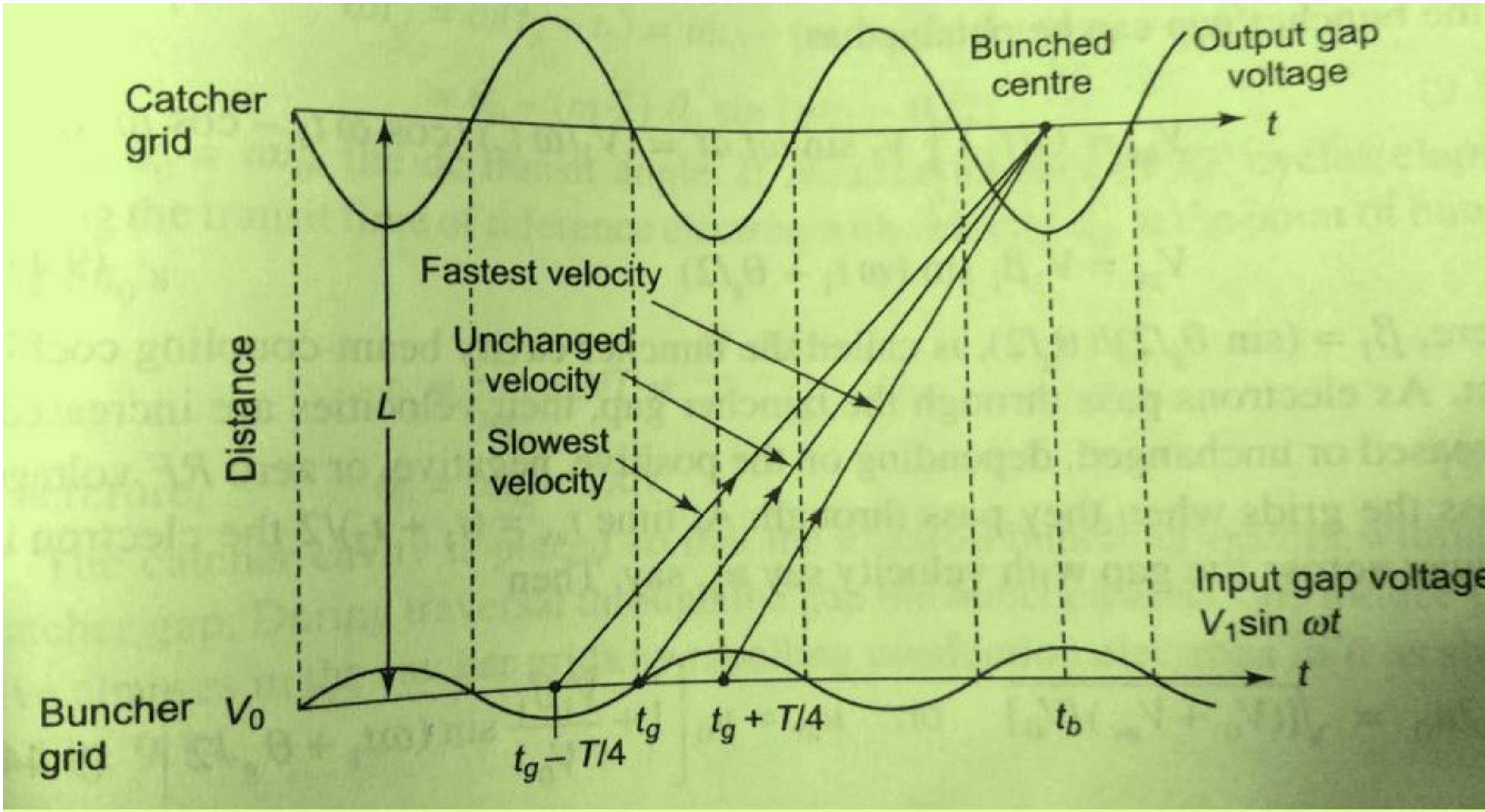


Buncher cavity action. ELECTRON #3 ACCELERATED.



Buncher cavity action. ELECTRONS BEGINNING TO BUNCH, DUE TO VELOCITY DIFFERENCES.

Velocity Modulation-Applegate Diagram



Characteristics

1. Pulsed Power: 30 MW @ 5GHz

2. Efficiency : 40%

3. Power Gain 30dB

Important parameters are,

- Velocity Modulation
- Klystron amplification
- Power output
- Efficiency

Reflex Klystrons

The reflex klystron has been the most used source of microwave power in laboratory applications.

Construction

- A reflex klystron consists of an electron gun, a cavity with a pair of grids and a repeller plate as shown in the above diagram.
- In this klystron, a single pair of grids does the functions of both the buncher and the catcher grids.
- The main difference between two cavity reflex klystron amplifier and reflex klystron is that the output cavity is omitted in reflex klystron and the repeller or reflector electrode, placed a very short distance from the single cavity, replaces the collector electrode.

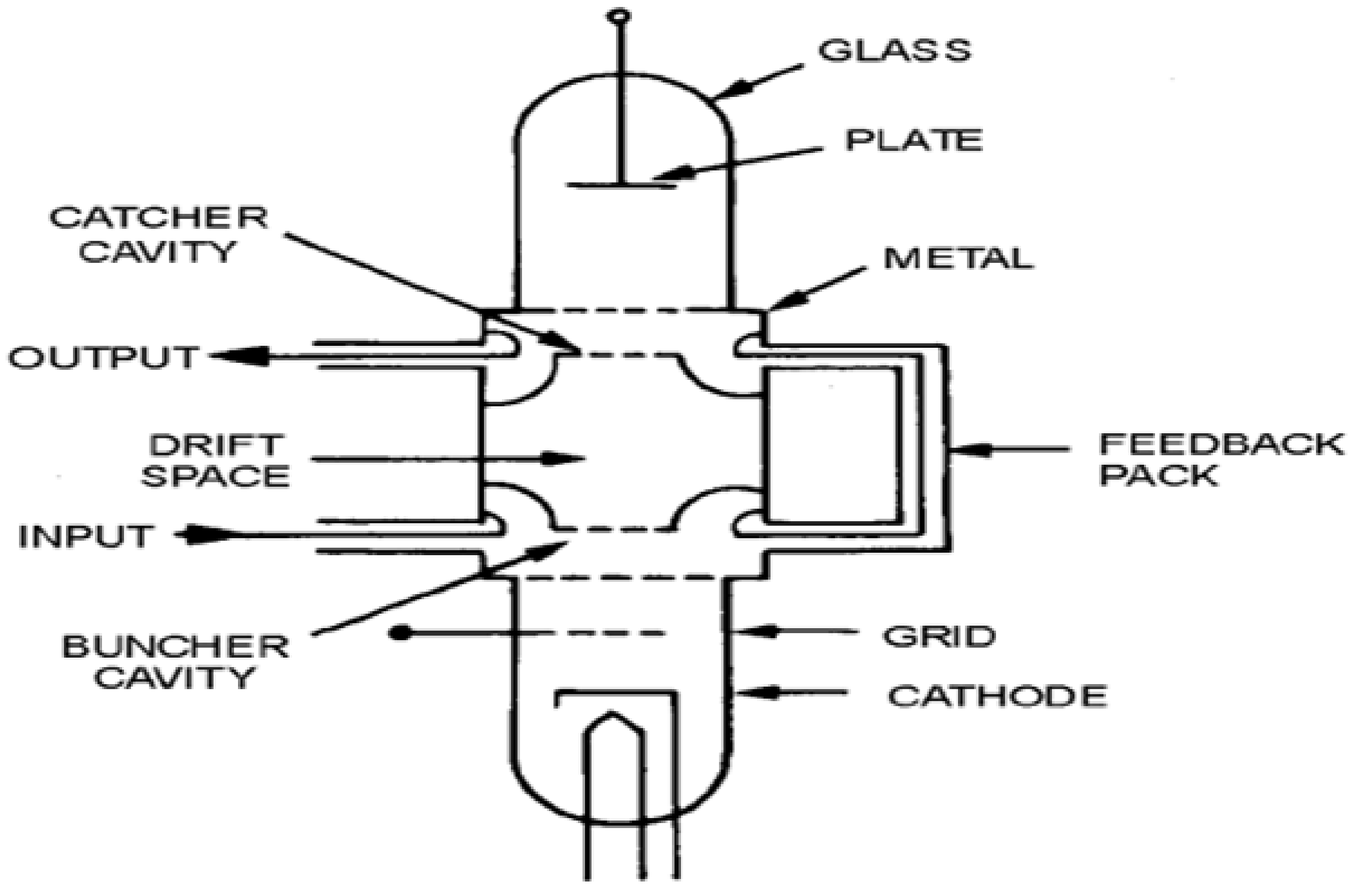
Working

- The cathode emits electrons which are accelerated forward by an accelerating grid with a positive voltage on it and focused into a narrow beam.

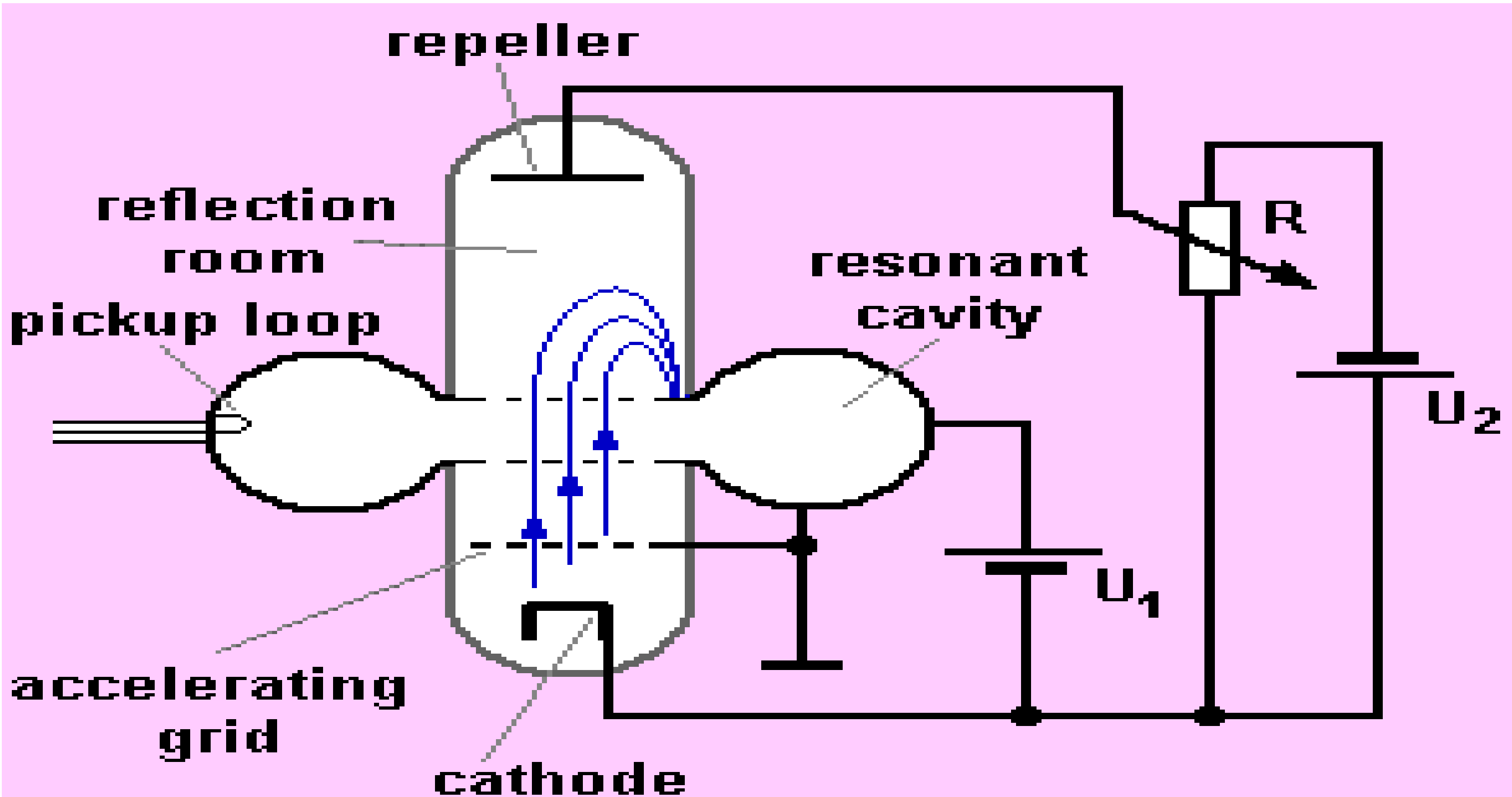
- The electrons pass through the cavity and undergo velocity modulation, which produces electron bunching and the beam is repelled back by a repeller plate kept at a negative potential with respect to the cathode.

- On return, the electron beam once again enters the same grids which act as a buncher, thereby the same pair of grids acts simultaneously as a buncher for the forward moving electron and as a catcher for the returning beam.

Functional and Schematic Diagram



Reflex Klystron oscillator



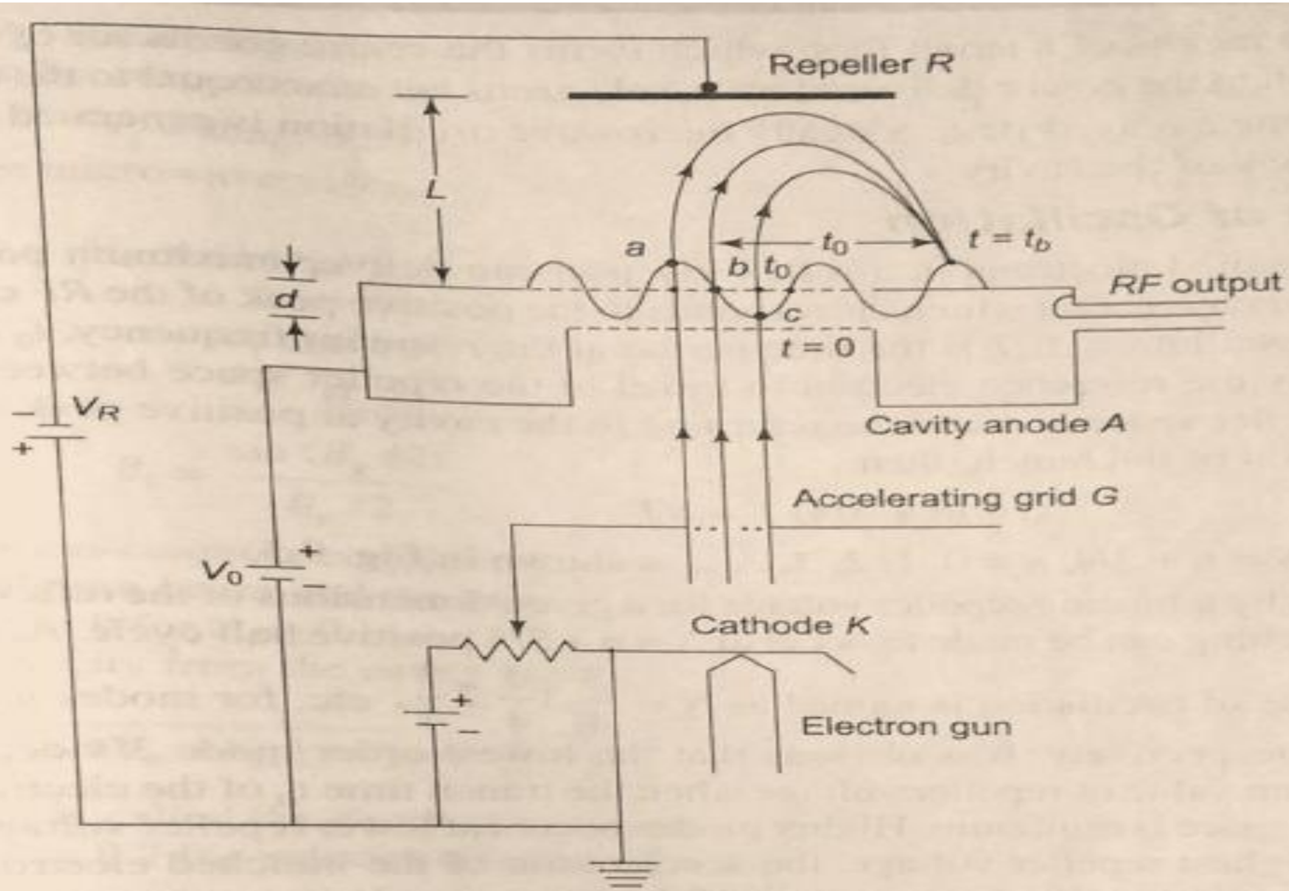
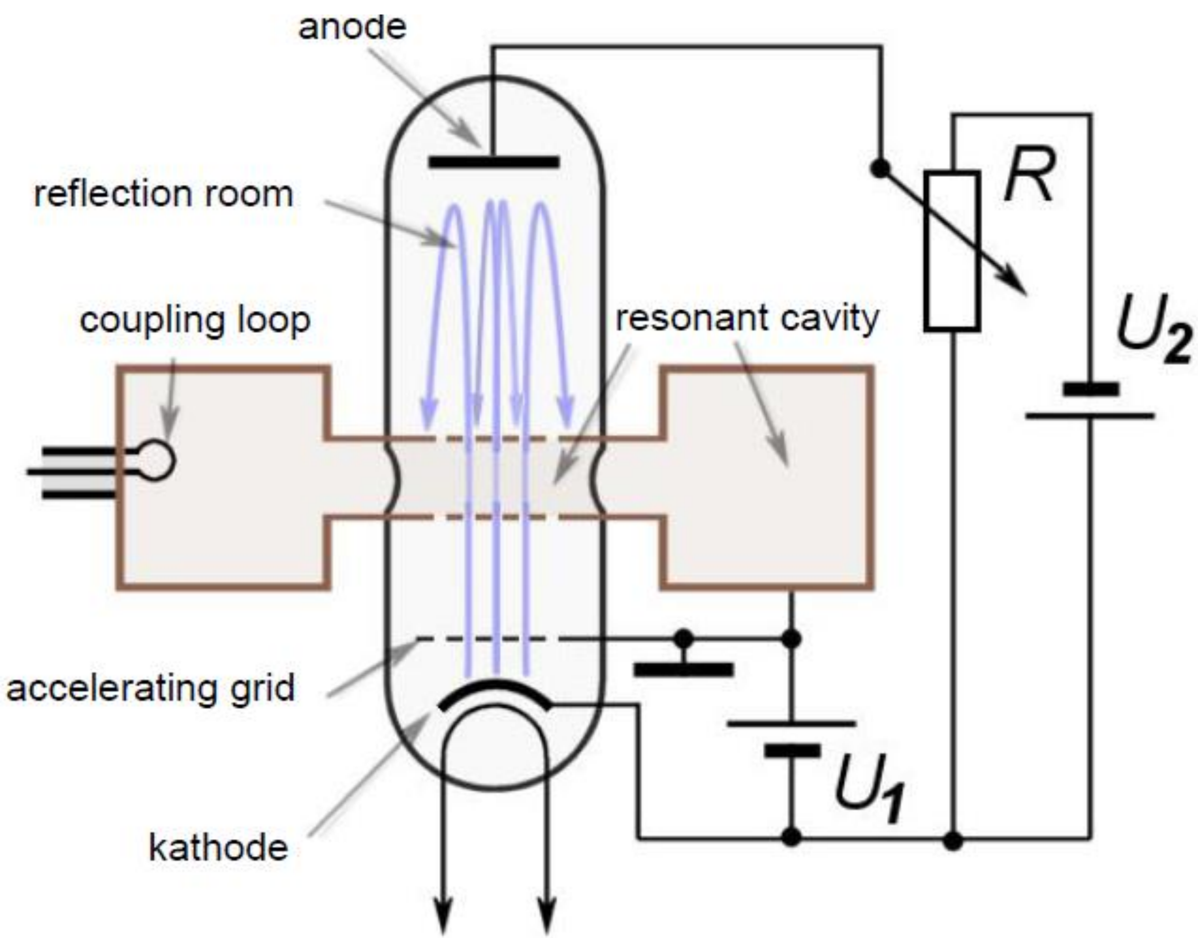


Fig. 9.4 *Reflex klystron operation*

Reflex Klystron oscillator



Working

- The feedback necessary for electrical oscillations is developed by reflecting the electron beam, the velocity modulated electron beam does not actually reach the repeller plate, but is repelled back by the negative voltage.
- The point at which the electron beam is turned back can be varied by adjusting the repeller voltage.
- Thus the repeller voltage is so adjusted that complete bunching of the electrons takes place at the catcher grids, the distance between the repeller and the cavity is chosen such that the repeller electron bunches will reach the cavity at proper time to be in synchronization.
- Due to this, they deliver energy to the cavity, the result is the oscillation at the cavity producing RF frequency.

Mode of Oscillation

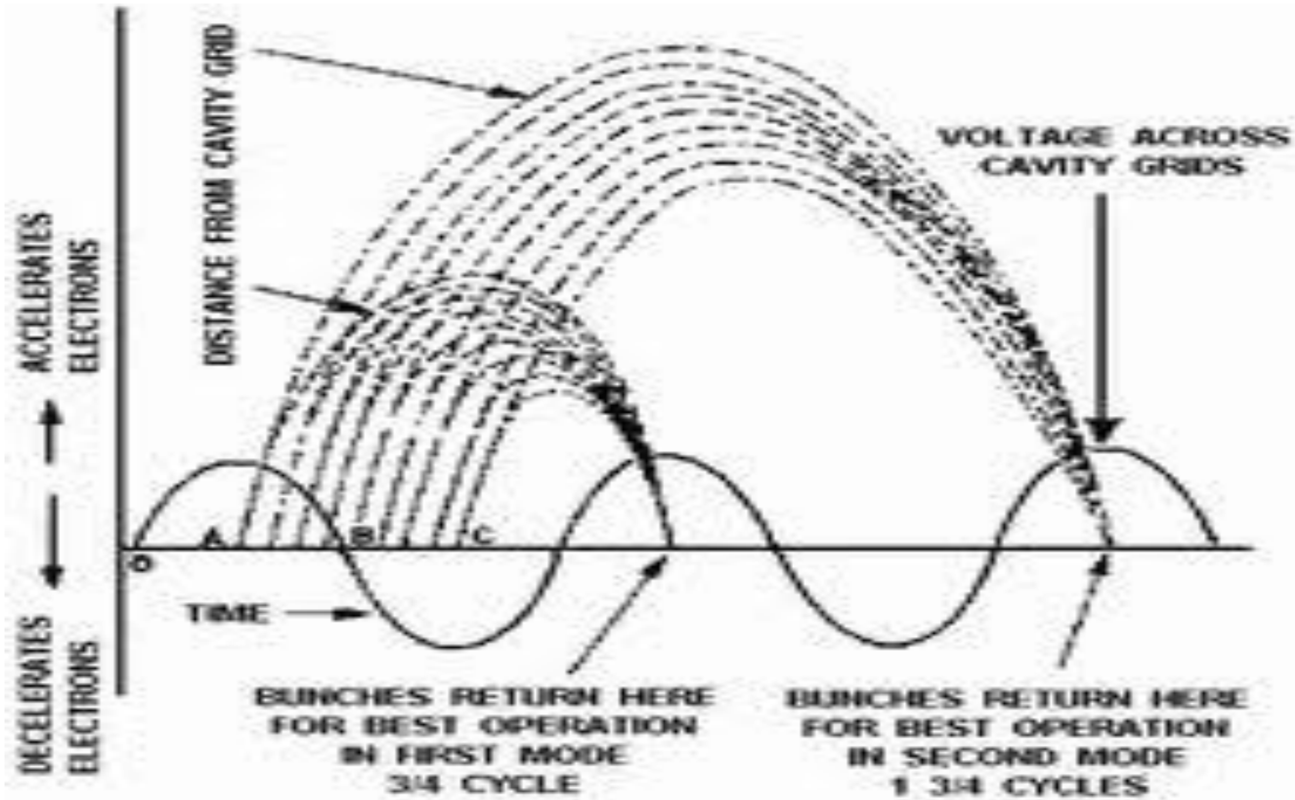
- The electrons should return after 1¾, 2 ¾ or 3 ¾ cycles – most optimum departure time.
- If **T is the time period at the resonant frequency**, t_o is the time taken by the reference electron to travel in the repeller space between entering the repeller space and returning to the cavity at positive peak voltage on formation of the bunch

Then, $t_o = (n + ¾)T = NT$

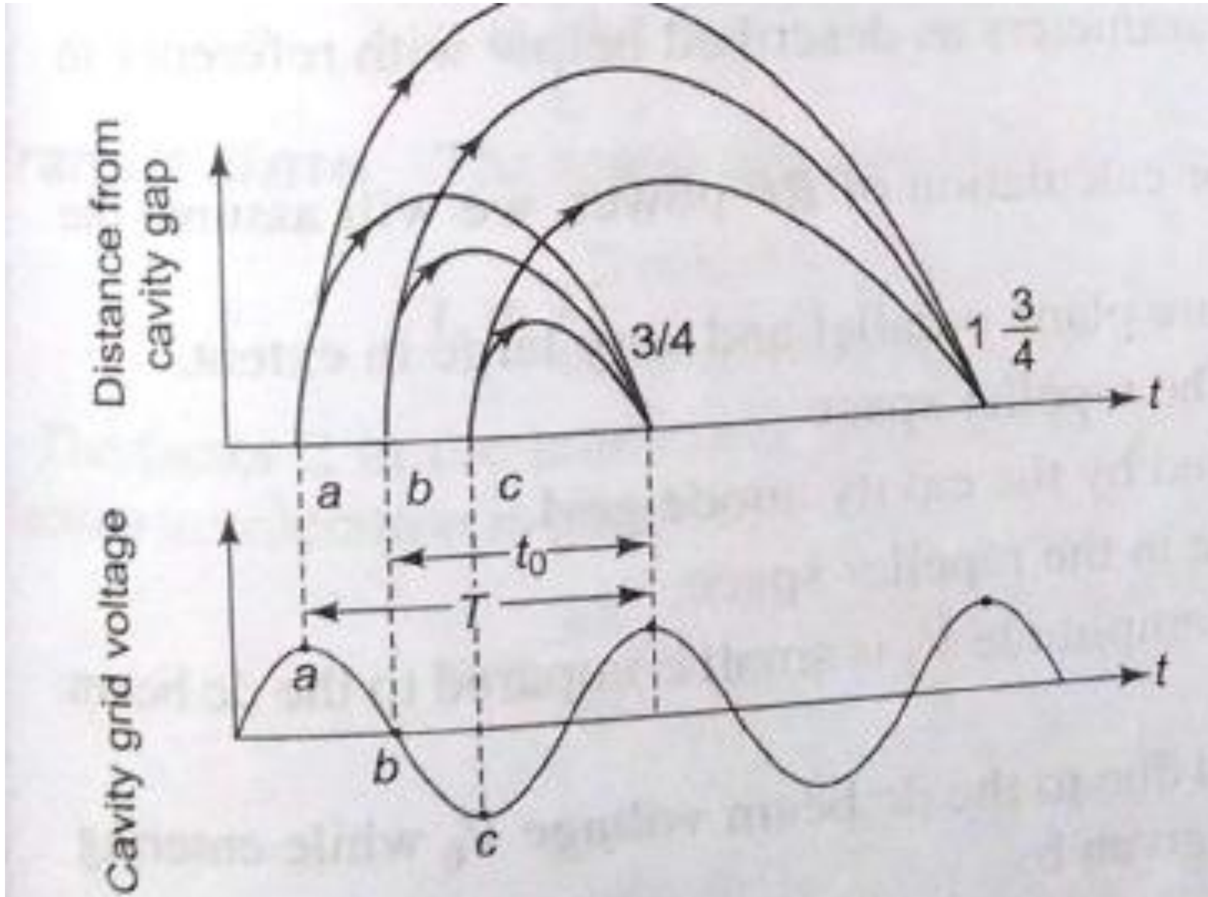
Where $N = n + ¾$, $n = 0,1,2,3…….$

N – mode of oscillation

Reflex Klystron Modes



Reflex Klystron modes



Performance Characteristics

1. Frequency: 4 – 200 GHz

2. Power: 1 mW – 2.5 W

3. Theoretical efficiency : 22.78 %

4. Practical efficiency : 10 % - 20 %

5. Tuning range : 5 GHz at 2 W – 30 GHz at 10 mW

Applications

The reflex klystrons are used in

1. Radar receivers
2. Local oscillator in microwave receivers
3. Signal source in microwave generator of variable frequency
4. Portable microwave links
5. Pump oscillator in parametric amplifier

Traveling Wave Tube

- Traveling Wave Tube (TWT) is the most versatile microwave RF power amplifiers.

- The main virtue of the TWT is its extremely wide band width of operation.

Slow wave structures

- Slow-wave structures are special circuits that are used in microwave tubes to reduce the wave velocity in a certain direction so that the electron beam and the signal wave can interact.
- The phase velocity of a wave in ordinary waveguides is greater than the velocity of light in a vacuum. In the operation of traveling-wave and magnetron-type devices, the electron beam must keep in step with the microwave signal.
- Since the electron beam can be accelerated only to velocities that are about a fraction of the velocity of light, a slow-wave structure must be incorporated in the microwave devices so that the phase velocity of the microwave signal can keep pace with that of the electron beam for effective interactions

Slow wave structures

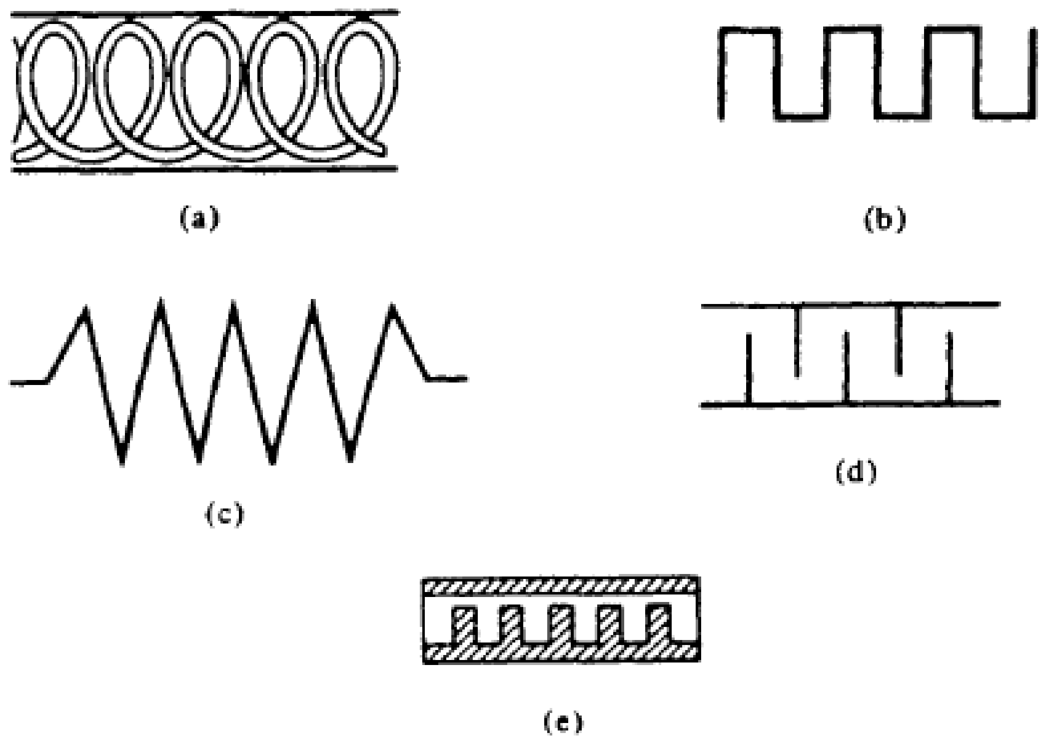
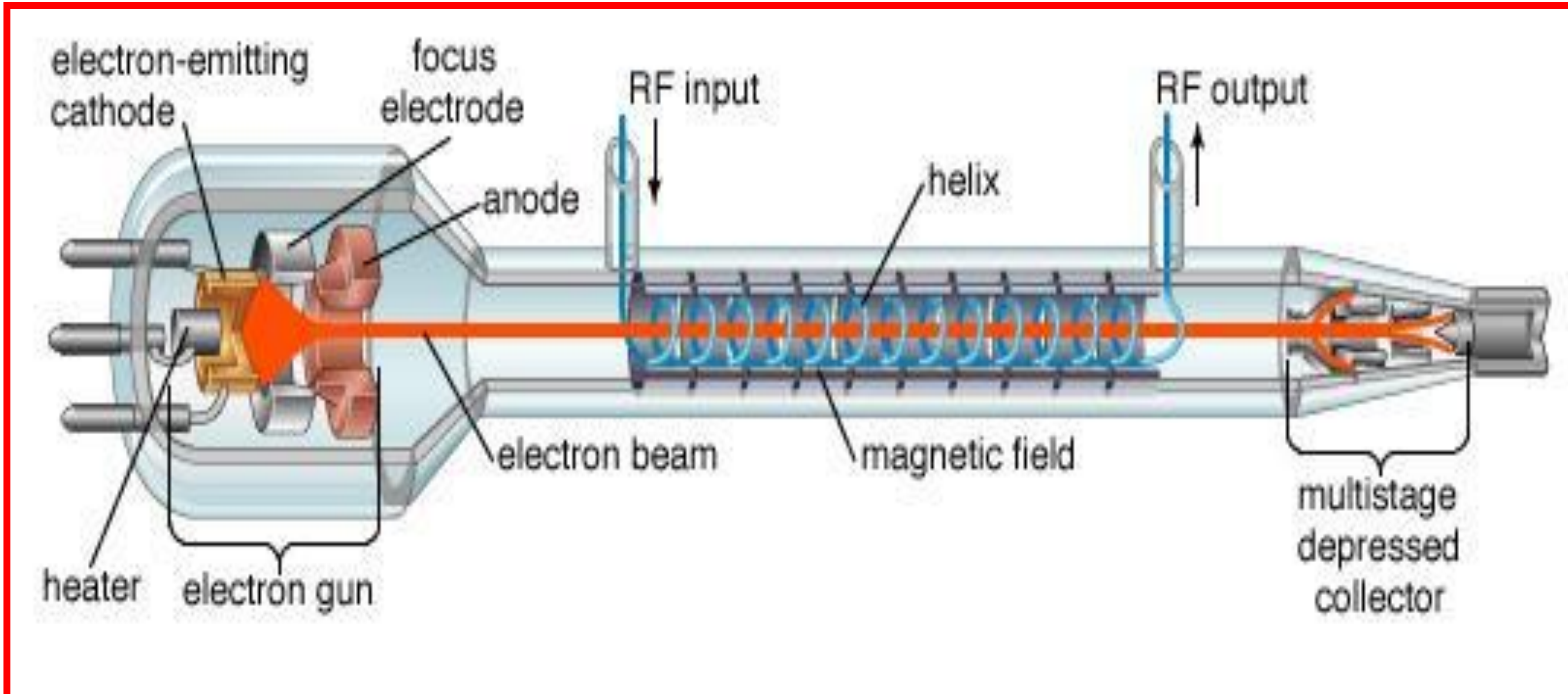


Figure 9-5-2 Slow-wave structures. (a) Helical line. (b) Folded-back line. (c) Zigzag line. (d) Interdigital line. (e) Corrugated waveguide.

Basic structure of a Traveling Wave Tube (TWT)



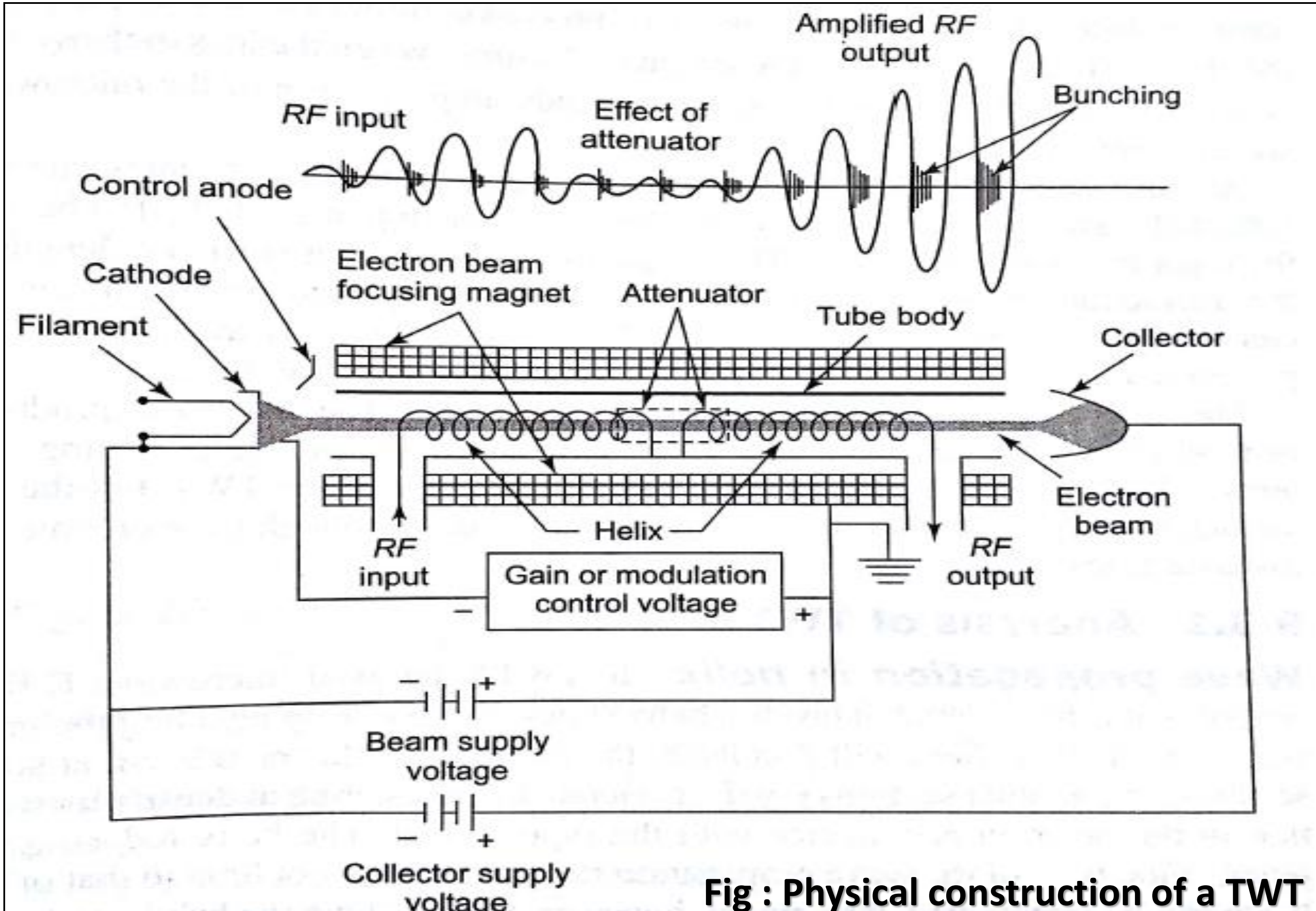
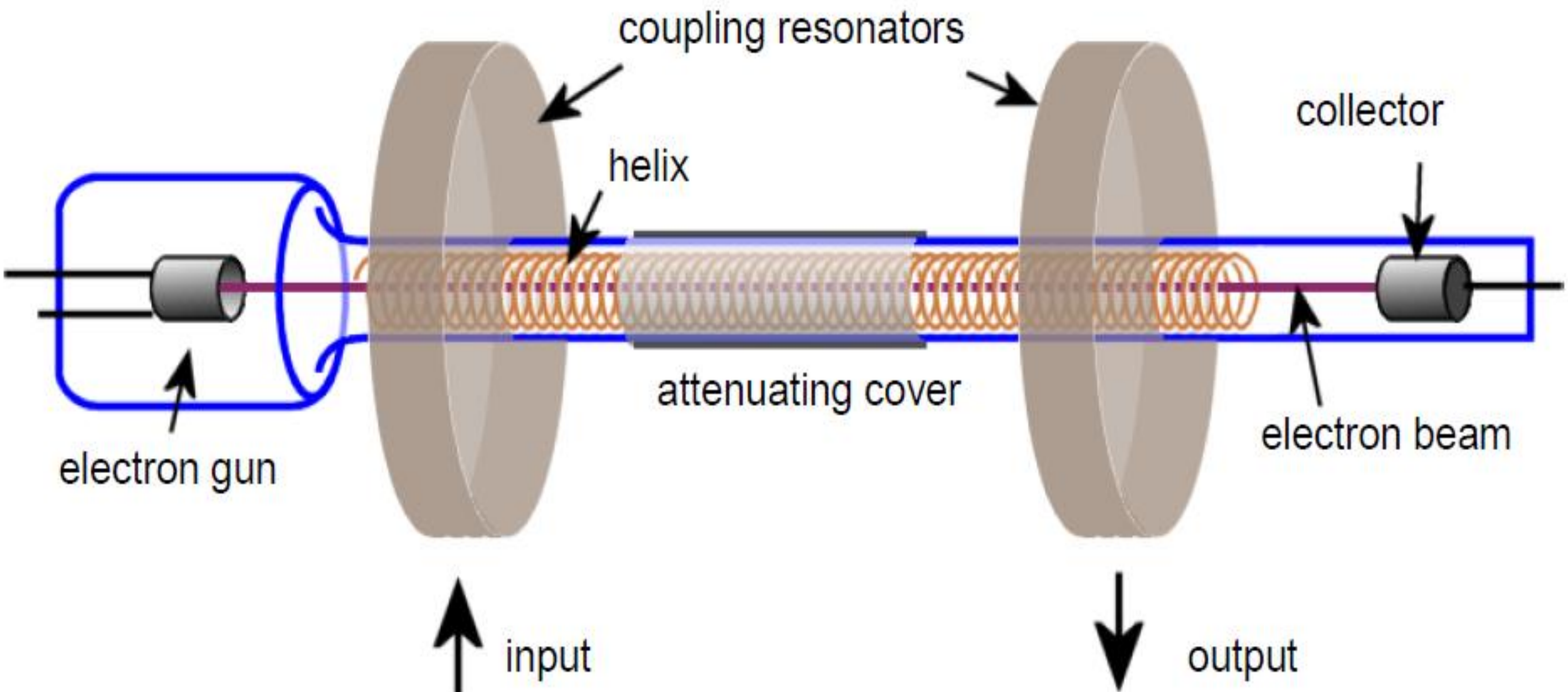


Fig : Physical construction of a TWT

Physical construction of a TWT



Basic structure

- The basic structure of a TWT consists of a cathode and filament heater plus an anode that is biased positively to accelerate the electron beam forward and to focus it into a narrow beam.
- The electrons are attracted by a positive plate called the collector, which has given a high dc voltage.
- The length of the tube is usually many wavelengths at the operating frequency.
- Surrounding the tube are either permanent magnets or electromagnets that keep the electrons tightly focused into a narrow beam.

Features

- The unique feature of the TWT is a helix or coil that surrounds the length of the tube and the electron beam passes through the center or axis of the helix.
- The microwave signal to be amplified is applied to the end of the helix near the cathode and the output is taken from the end of the helix near the collector.
- The purpose of the helix is to provide path for RF signal.
- The propagation of the RF signal along the helix is made approximately equal to the velocity of the electron beam from the cathode to the collector

Functioning

- The passage of the microwave signal down the helix produces electric and magnetic fields that will interact with the electron beam.
- The electromagnetic field produced by the helix causes the electrons to be speeded up and slowed down, this produces velocity modulation of the beam which produces density modulation.
- Density modulation causes bunches of electrons to group together one wavelength apart and these bunch of electrons travel down the length of the tube toward the collector.

Functioning

- The electron bunches induce voltages into the helix which reinforce the voltage already present there. Due to that the strength of the electromagnetic field on the helix increases as the wave travels down the tube towards the collector.

- At the end of the helix, the signal is considerably amplified. Coaxial cable or waveguide structures are used to extract the energy from the helix.

Advantages

1. TWT has extremely wide bandwidth. Hence, it can be made to amplify signals from UHF to hundreds of gigahertz.
2. Most of the TWT's have a frequency range of approximately 2:1 in the desired segment of the microwave region to be amplified.
3. The TWT's can be used in both continuous and pulsed modes of operation with power levels up to several thousands watts.

Performance characteristics

1. Frequency of operation : 0.5 GHz – 95 GHz
2. Power outputs:

   5 mW (10 – 40 GHz – low power TWT)

   250 kW (CW) at 3 GHz (high power TWT)

   10 MW (pulsed) at 3 GHz
3. Efficiency : 5 – 20 % (30 % with depressed collector)

Diff b/w Klystron and TWTA

KLYSTRON AMPLIFIER	TWTA
Linear beam or ‘O’ type device	Linear beam or ‘O’ type device
Uses Cavities fro input and output circuits	Uses non resonant wave circuits
Narrow band device due to use of resonant cavities	Wideband device because use of non-resonant wave circuit

Applications of TWT

1. Low noise RF amplifier in broad band microwave receivers.
2. Repeater amplifier in wide band communication links and long distance telephony.
3. Due to long tube life (50,000 hours against ¼th for other types), TWT is power output tube in communication satellite.
4. Continuous wave high power TWT's are used in troposcatter links (due to larger power and larger bandwidths).
5. Used in Air borne and ship borne pulsed high power radars.

CROSSED-FIELD TUBES (M-TYPE TUBES)

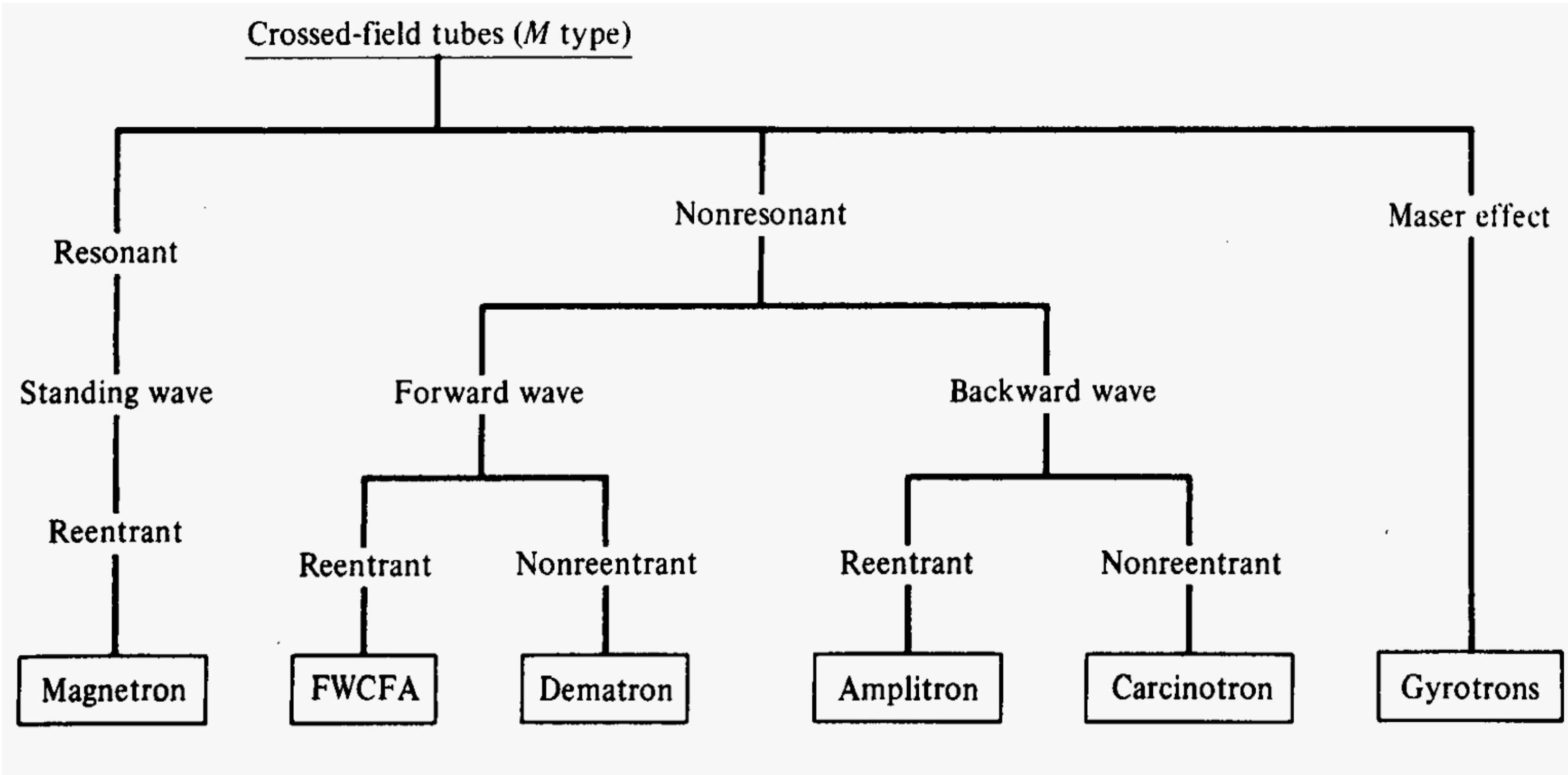
Introduction

- In linear beam tubes like Klystron or Travelling wave tube (TWT) , the dc Magnetic field parallel to the dc Electric field is used to focus the electron beam .
- Crossed-field tubes derive their name from the fact that the dc magnetic field is perpendicular to the dc electric field . In this tubes, the dc magnetic field plays a direct role in the RF interaction process.
- These tubes are also called *M-Type tubes*.
- In a crossed-field tube, the electrons emitted by the cathode are accelerated by the electric field and gain velocity , but the greater their velocity , the more their path is bent by the magnetic field.

Cross-Field Effect:

- In a crossed-field tube, the electrons emitted by the cathode are accelerated by the electric field and gain velocity , but the greater their velocity , the more their path is bent by the magnetic field.
- If an RF field is applied to the circuit , those electrons entering the circuit during retarding field are decelerated and give up some of their kinetic energy to the RF field. Consequently , their velocity is decreased and these slower electrons will then travel the dc electric field far enough to regain essentially the same velocity as before.
- Because of crossed-field interactions, only those electrons that have given up sufficient energy to the RF field can travel all the way to the anode. This phenomenon would make the *M*-type devices relatively efficient.
- Those electrons entering the circuit during the accelerating field are accelerated by means of receiving enough energy from the RF field and are returned back towards the cathode. This back bombardment of the cathode produces heat in the cathode and decreases the operational efficiency.

- The classification of crossed-field tubes is,



Magnetron Oscillators

- Hull invented magnetron, but it was only on interesting laboratory device.
- During the world war II an urgent need for high power microwave generators for RADAR transmitters led to the rapid development of Magnetron
- Magnetrons provide microwave oscillations of very high frequency
- All magnetrons consists of some form of anode & cathode operated in dc Magnetic field between cathode & anode.
- Because of cross field between cathode & anode , the electrons emitted from cathode are influenced by the cross field to move in a curved path.
- If the dc magnetic field is strong enough the electrons will not arrive at in the anode but return to the cathode, consequently anode current is cutoff.

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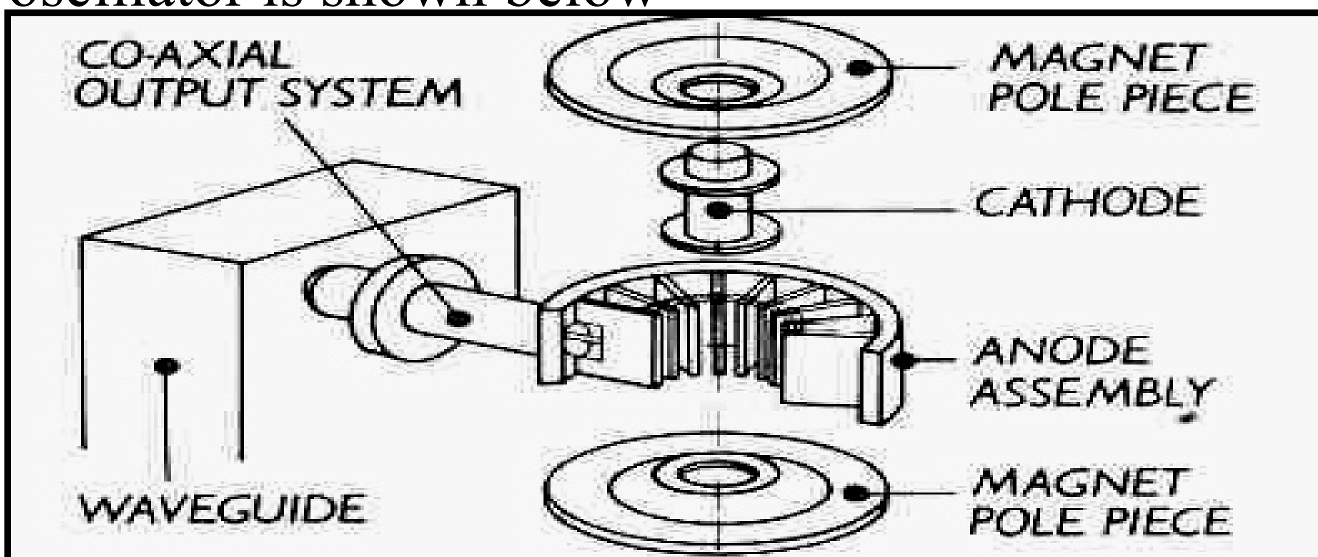
- Magnetrons can be classified in to three types as follows,

  1. *Negative resistance Magnetrons or Split-Anode Magnetron :*
     - Make use of static negative resistance between two anode segments. Low efficiency and are useful only at low frequencies (< 500 MHz).
  2. *Cyclotron-frequency Magnetrons :*
     - Operates under the influence of synchronism between an alternating component of electric field and periodic oscillation of electrons in a direction parallel to this field.
     - Useful only for frequencies greater than 100 MHz
  3. *Cavity or Traveling-wave Magnetrons :*
     - Depends upon the interaction of electrons with a traveling electromagnetic field of linear velocity.
     - These are customarily referred as *Magnetrons*
     - Provide oscillations of very high peak power and hence are useful in radar applications

Cylindrical Magnetrons

- Cylindrical magnetron Oscillator is also called as conventional Magnetron.
- In a cylindrical magnetron , several reentrant cavities are connected to the gaps and hence some times called as Cavity Magnetron.
- Schematic diagram illustrating the major elements of the magnetron oscillator is shown below



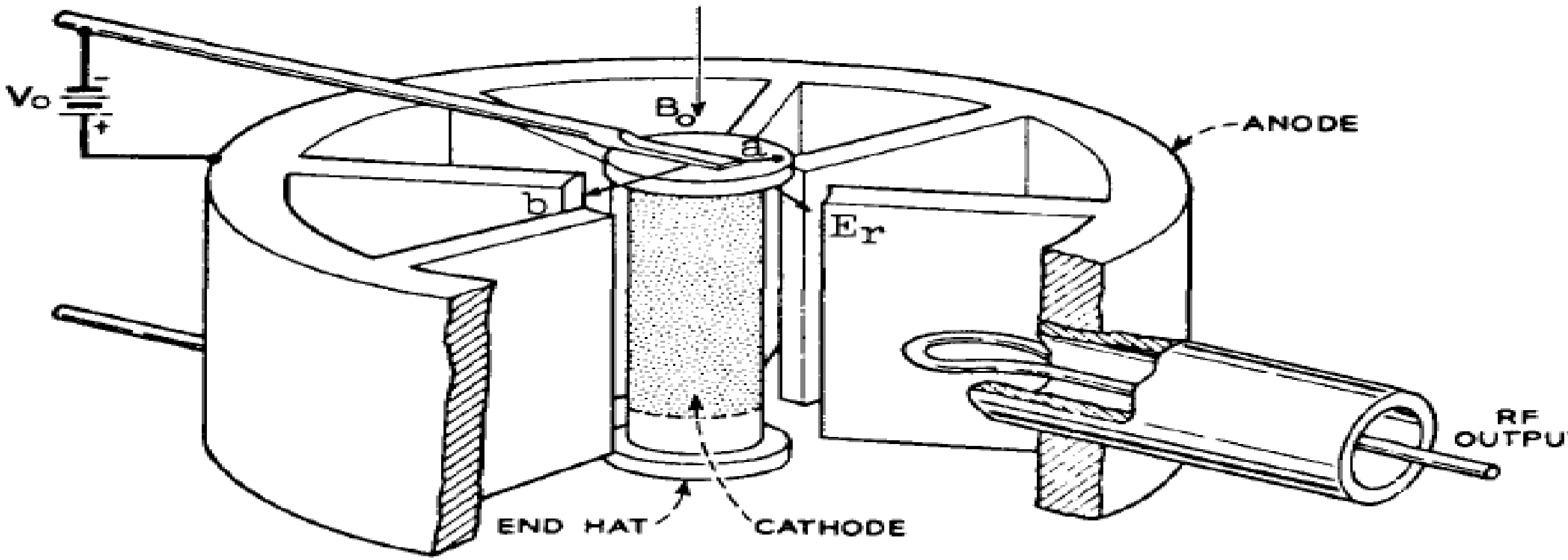


Figure 10-1-1 Schematic diagram of a cylindrical magnetron.

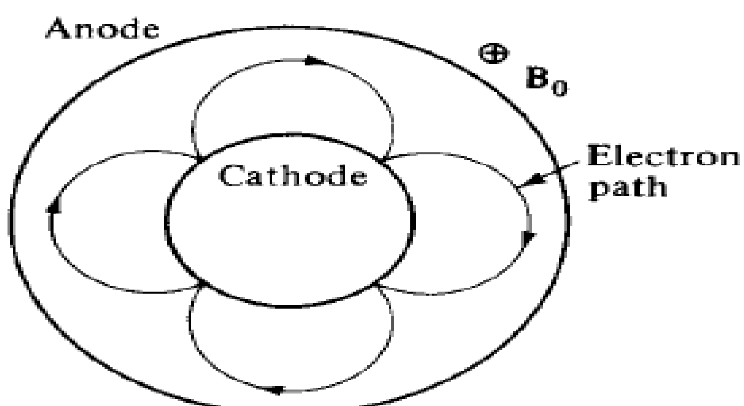
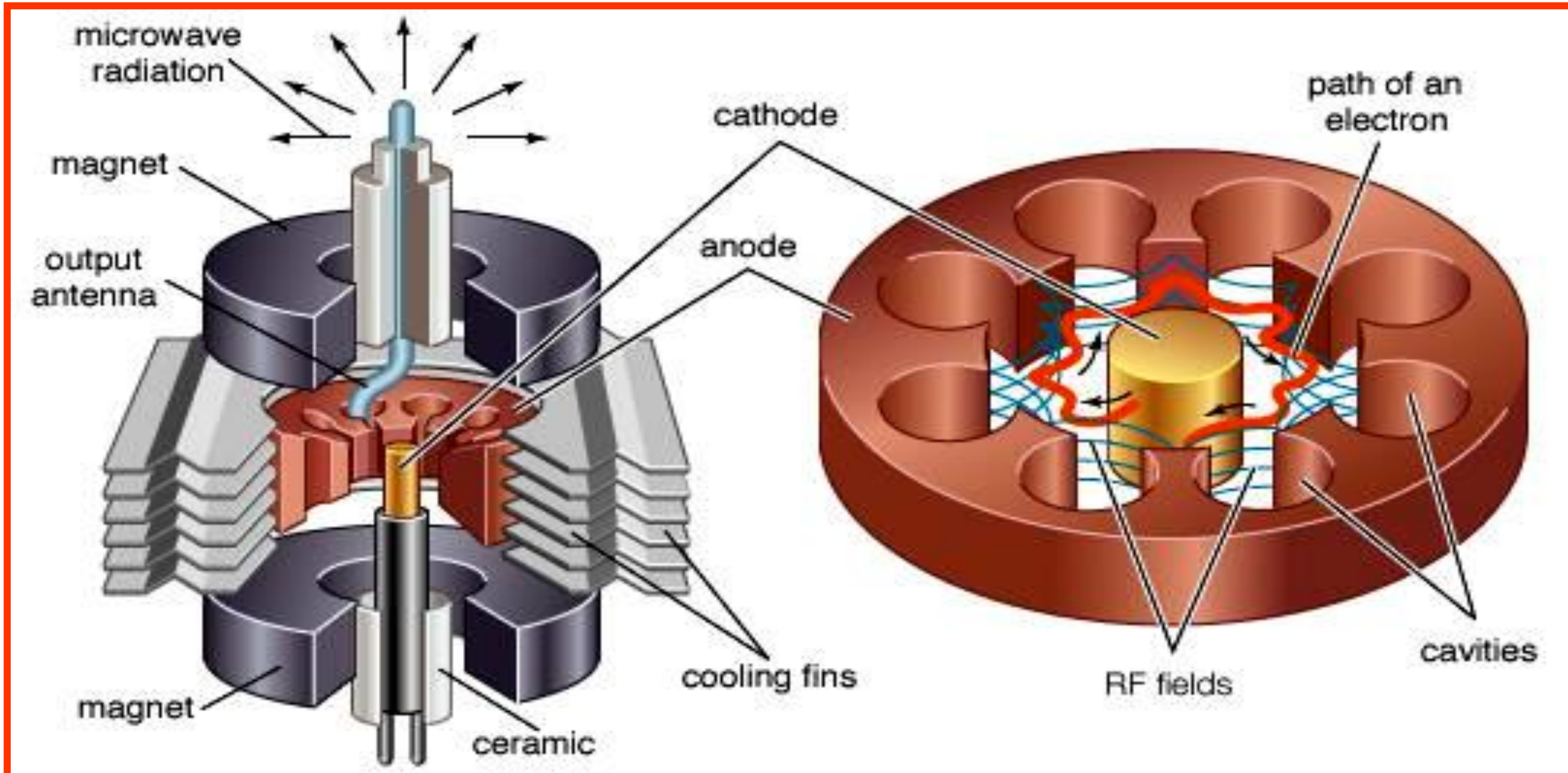


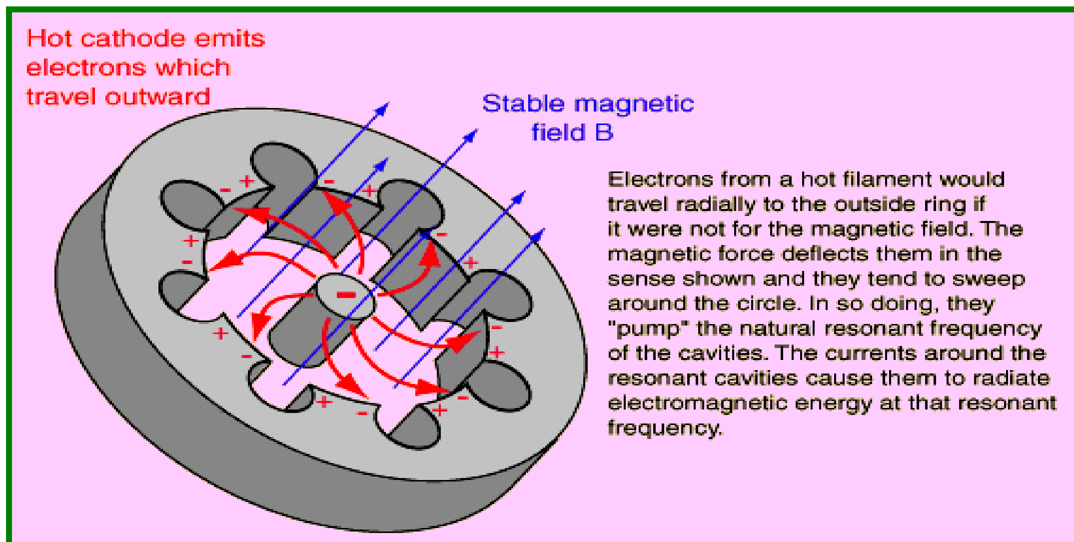
Figure 10-1-2 Electron path in a cylindrical magnetron.

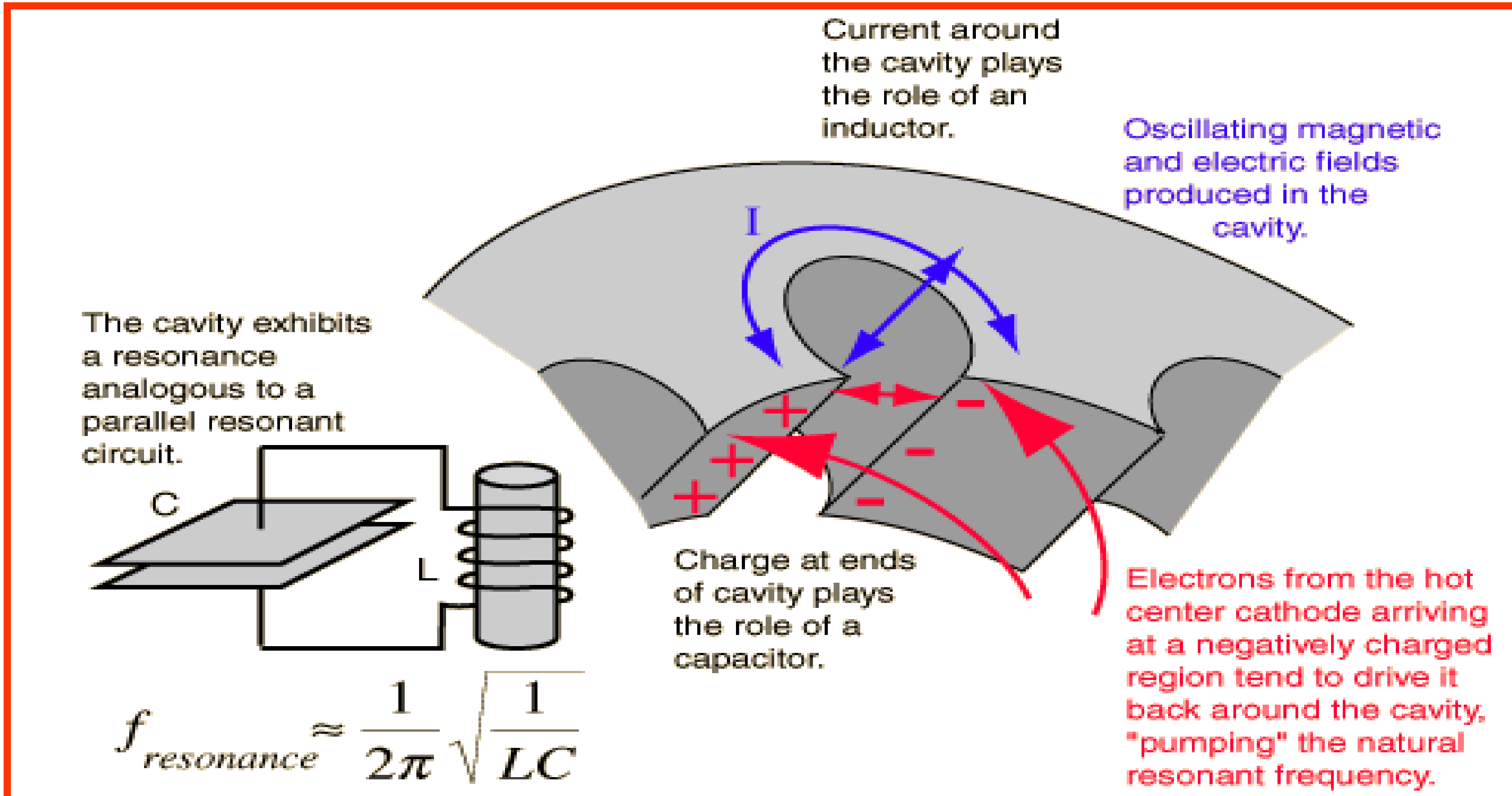
- The detailed diagram of cavity magnetrons is,



Construction:

- Each cavity in the anode acts as an inductor having only one turn and the slot connecting the cavity and the interaction space acts as a capacitor.
- These two form a parallel resonant circuit and its resonant frequency depends on the value of *L* of the cavity and the *C* of the slot.
- The frequency of the microwaves generated by the magnetron oscillator depends on the frequency of the RF oscillations existing in the resonant cavities. Cross sectional view of anode assembly can be viewed as,

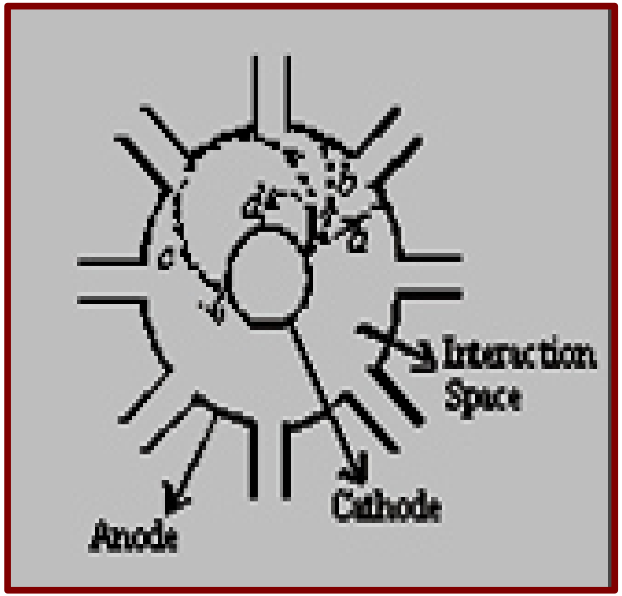


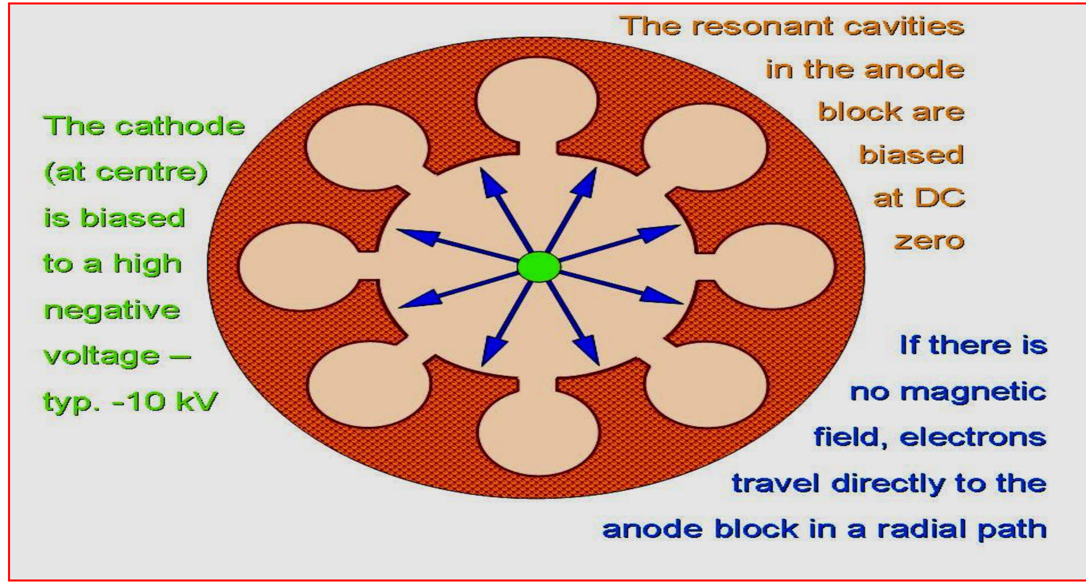

Current around the cavity plays the role of an inductor.
Oscillating magnetic and electric fields produced in the cavity.
I
The cavity exhibits a resonance analogous to a parallel resonant circuit.
C
L
Charge at ends of cavity plays the role of a capacitor.
Electrons from the hot center cathode arriving at a negatively charged region tend to drive it back around the cavity, "pumping" the natural resonant frequency.
$f_{resonance} \approx \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$

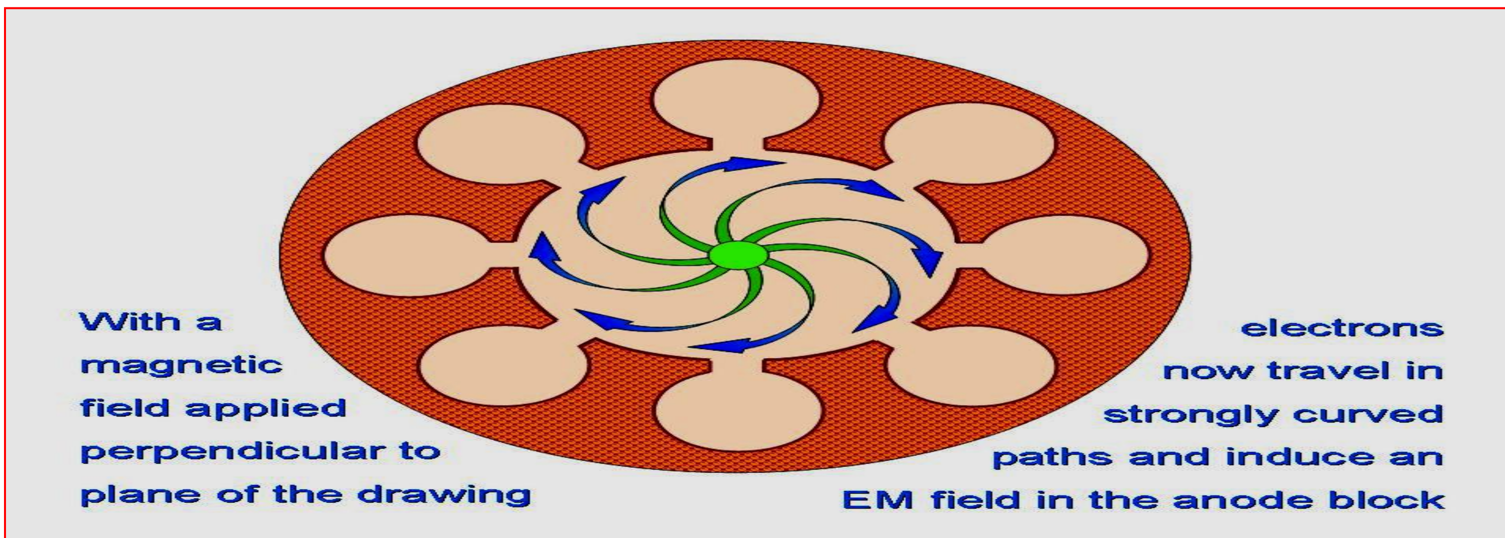
Working principle:

- Magnetron is a cross field device as the electric field between the anode and the cathode is radial whereas the magnetic field produced by a permanent magnet is axial.
- A high dc potential can be applied between the cathode and anode which produces the radial electric field.
- Depending on the relative strengths of the electric and magnetic fields, the electrons emitted from the cathode and moving towards the anode will traverse through the interaction space.
- In the absence of magnetic field ($B = 0$), the electron travel straight from the cathode to the anode due to the radial electric field force acting on it as given by the path 'a' in the following figure.
- If the magnetic field strength is increased slightly, the lateral force bending the path of the electron as given by the path '*b*' in the following figure.

- The radius of the path is given by, if the strength of the magnetic field is made sufficiently high , then the electrons can be prevented from reaching the anode as indicated path '*c*' in figure shown below.
- The magnetic field required to return electrons back to the cathode just grazing the surface of the anode is called the *critical magnetic field (B_c) or the cut-off magnetic field.*
- If the magnetic field is larger than the critical field ($B > B_c$), the electron experiences a greater rotational force and may return back to the cathode quite faster.
- The various motion of electrons in the presence of different magnitudes of magnetic field can be viewed in the following figures,

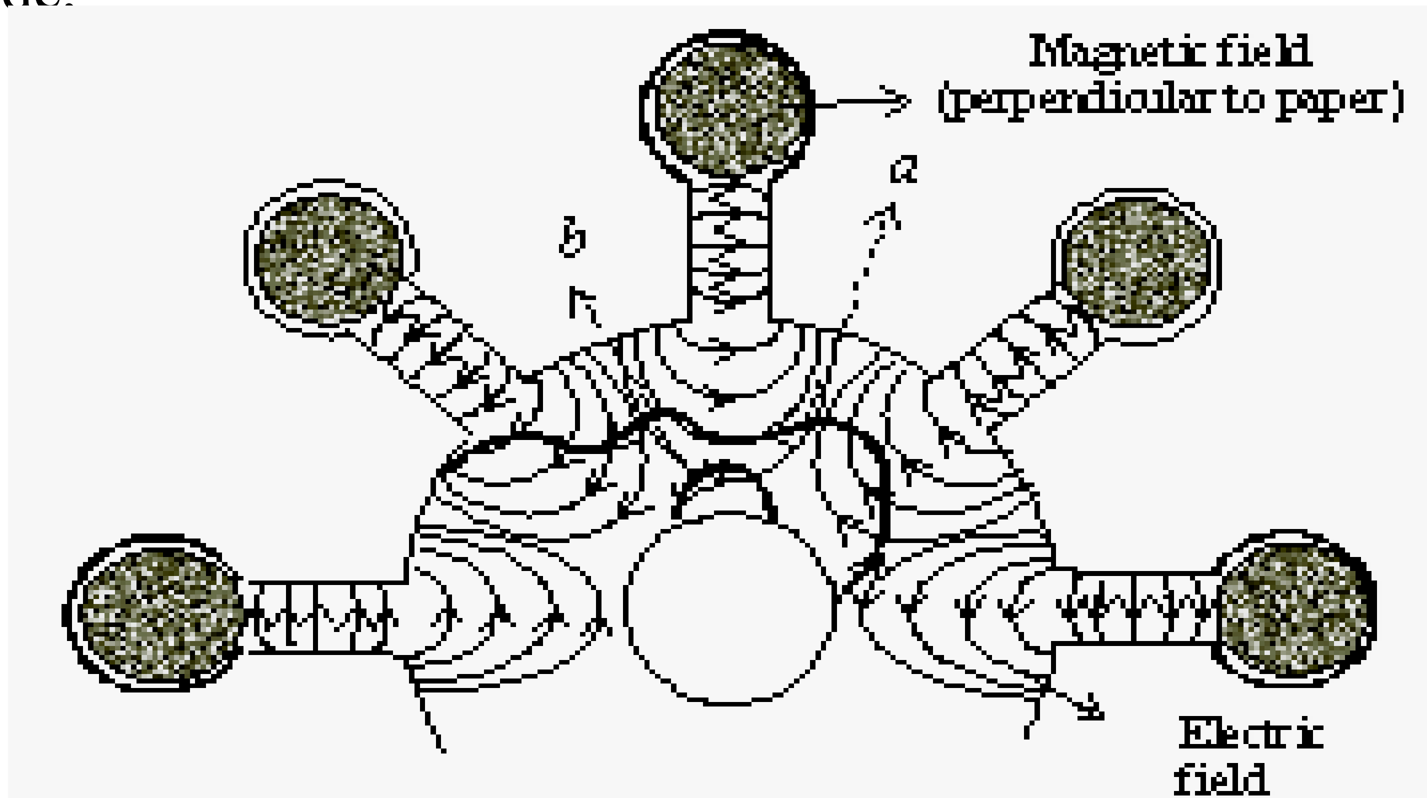

Interaction Space
Cathode
Anode


The resonant cavities in the anode block are biased at DC zero
The cathode (at centre) is biased to a high negative voltage – typ. -10 kV
If there is no magnetic field, electrons travel directly to the anode block in a radial path


With a magnetic field applied perpendicular to plane of the drawing
electrons now travel in strongly curved paths and induce an EM field in the anode block

- The RF oscillations of transient nature produced when the HT is switched on, are sufficient to produce the oscillations in the cavities, these oscillations are maintained in the cavities reentrant feedback which results in the production of microwaves.
- Reentrant feedback takes place as a result of interaction of the electrons with the electric field of the RF oscillations existing in the cavities.
- The cavity oscillations produce electric fields which fringe out into the interaction space from the slots in the anode structure, as shown in figure , which illustrates possible trajectory of electrons from cathode to anode in an eight cavity magnetron operating in π mode .
- Energy is transferred from the radial dc field to the RF field by the interaction of the electrons with the fringing RF field.
- Due to the oscillations in the cavities, the either sides of the slots (which acts as a capacitor) becomes alternatively positive and negative and hence the directions of the electric field across the slot also reverse its sign alternatively.

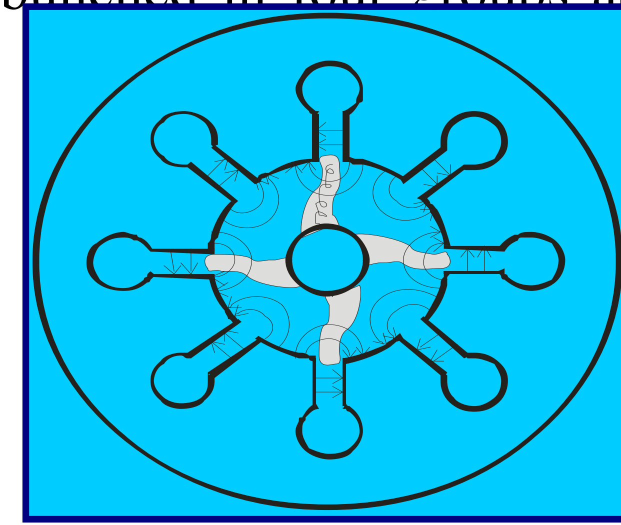
- The following figure illustrates possible trajectory of electrons from cathode to anode in an eight cavity magnetron operating in π mode.



- At any instant the anode close to the spiraling electron goes positive, the electrons gets retarded and this is because; the electron has to move in the RF field, existing close to the slot, from positive side to the negative side of the slot.
- In this process, the electron loses energy and transfer an equal amount of energy to the RF field which retard the spiraling electron.
- On return to the previous orbit the electron may reach the adjacent section or a section farther away and transfer energy to the RF field if that part of the anode goes positive at that instant.
- This electron travels in a longest path from cathode to the anode as indicated by *'a'* in above Figure , transferring the energy to the RF field are called as *favored electrons* and are responsible for bunching effect and give up most of its energy before it finally terminates on the anode surface.
- An electron '*b*' is accelerated by the RF field and instead of imparting energy to the oscillations, takes energy from oscillations resulting in increased velocity, such electrons are called *unfavored electrons* which do not participate in the bunching process and cause back heating.

- Every time an electron approaches the anode "in phase" with the RF signal, it completes a cycle. This corresponds to a phase shift 2π.
- For a dominant mode, the adjacent poles have a phase difference of π radians, this called the π - mode.
- At any particular instant, one set of alternate poles goes positive and the remaining set of alternate poles goes negative due to the RF oscillations in the cavities.
- As the electron approaches the anode, one set of alternate poles accelerates the electrons and turns back the electrons quickly to the cathode and the other set alternate poles retard the electrons, thereby transferring the energy from electrons to the RF signal.
- This process results in the bunching of electrons, the mechanism by which electron bunches are formed and by which electrons are kept in synchronism with the RF field is called ***phase focusing effect.***

- The number of bunches depends on the number of cavities in the magnetron and the mode of oscillations. In an eight cavity magnetron oscillating with π - mode, the electrons are bunched in four groups as shown in following figure.



- Two identical resonant cavities will resonate at two frequencies when they are coupled together; this is due to the effect of mutual coupling.
- Commonly separating the *pi mode* from adjacent modes is by a method called *strapping*. The straps consist of either circular or rectangular cross section connected to alternate segments of the anode block.

Hull cutoff Magnetic Equation:

- The equation for the cutoff magnetic field can be obtained by considering the equations for the motion of electrons in the cylindrical magnetron which can be written as

$$\frac{d^2r}{dt^2} - r\left(\frac{d\phi}{dt}\right)^2 = \frac{e}{m}E_r - \frac{e}{m}rB_z\frac{d\phi}{dt} \tag{10-1-1}$$

$$\frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\phi}{dt}\right) = \frac{e}{m}B_z\frac{dr}{dt} \tag{10-1-2}$$

where $\frac{e}{m} = 1.759 \times 10^{11}$ C/kg is the charge-to-mass ratio of the electron and $B_0 = B_z$ is assumed in the positive z direction.

Rearrangement of Eq. (10-1-2) results in the following form

$$\frac{d}{dt}\left(r^2\frac{d\phi}{dt}\right) = \frac{e}{m}B_z r\frac{dr}{dt} = \frac{1}{2}\omega_c\frac{d}{dt}(r^2) \tag{10-1-3}$$

where $\omega_c = \frac{e}{m}B_z$ is the cyclotron angular frequency.

Integration of Eq. (10-1-3) yields

$$r^2 \frac{d\phi}{dt} = \frac{1}{2}\omega_c r^2 + \text{constant} \tag{10-1-4}$$

at $r = a$, where a is the radius of the cathode cylinder, and $\frac{d\phi}{dt} = 0$, constant $= -\frac{1}{2}\omega_c a^2$. The angular velocity is expressed by

$$\frac{d\phi}{dt} = \frac{1}{2}\omega_c\left(1 - \frac{a^2}{r^2}\right) \tag{10-1-5}$$

Since the magnetic field does no work on the electrons, the kinetic energy of the electron is given by

$$\frac{1}{2}m\mathcal{V}^2 = eV \tag{10-1-6}$$

However, the electron velocity has r and ϕ components such as

$$\mathcal{V}^2 = \frac{2e}{m}V = \mathcal{V}_r^2 + \mathcal{V}_\phi^2 = \left(\frac{dr}{dt}\right)^2 + \left(r\frac{d\phi}{dt}\right)^2 \tag{10-1-7}$$

at $r = b$, where b is the radius from the center of the cathode to the edge of the anode, $V = V_0$, and $dr/dt = 0$, when the electrons just graze the anode, Eqs. (10-1-5) and (10-1-7) become

$$\frac{d\phi}{dt} = \frac{1}{2}\omega_c\left(1 - \frac{a^2}{b^2}\right) \tag{10-1-8}$$

$$b^2\left(\frac{d\phi}{dt}\right)^2 = \frac{2e}{m}V_0 \tag{10-1-9}$$

Substitution of Eq. (10-1-8) into Eq. (10-1-9) results in

$$b^2\left[\frac{1}{2}\omega_c\left(1 - \frac{a^2}{b^2}\right)\right]^2 = \frac{2e}{m}V_0 \tag{10-1-10}$$

The electron will acquire a tangential as well as a radial velocity. Whether the electron will just graze the anode and return toward the cathode depends on the relative magnitudes of V_0 and B_0. The *Hull cutoff magnetic equation* is obtained from Eq. (10-1-10) as

$$B_{0c} = \frac{\left(8V_0\dfrac{m}{e}\right)^{1/2}}{b\left(1 - \dfrac{a^2}{b^2}\right)} \tag{10-1-11}$$

This means that if $B_0 > B_{0c}$ for a given V_0, the electrons will not reach the anode. Conversely, the cutoff voltage is given by

$$V_{0c} = \frac{e}{8m}B_0^2 b^2\left(1 - \frac{a^2}{b^2}\right)^2 \tag{10-1-12}$$

This means that if $V_0 < V_{0c}$ for a given B_0, the electrons will not reach the anode. Equation (10-1-12) is often called the *Hull cutoff voltage equation*.

Hartree Condition:

- The Hull cutoff condition determines the anode voltage or magnetic field necessary to obtain nonzero anode current as a function of the magnetic field or anode voltage in the absence of an electromagnetic field. The Hartree condition can be derived as follows and as shown in the following figure 10-1-9.

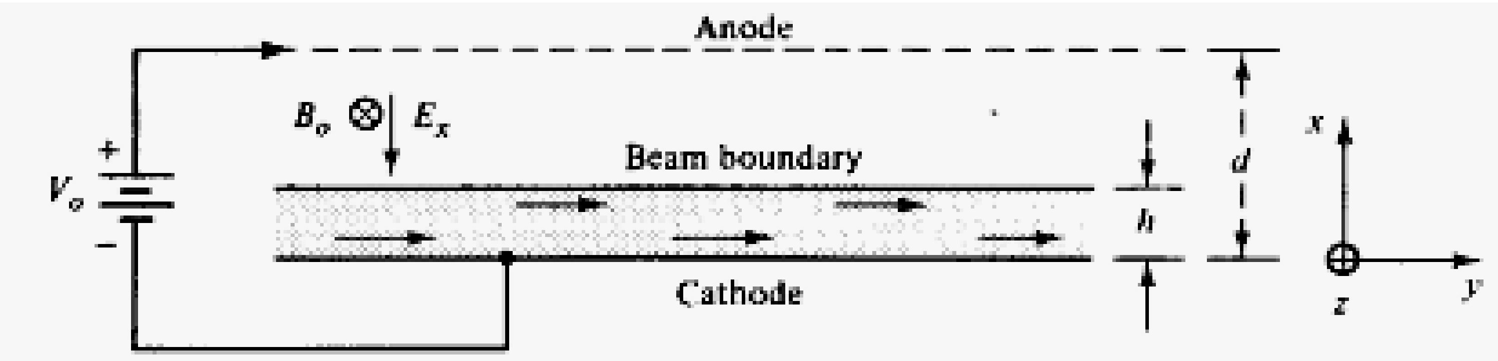


Figure 10-1-9 Linear model of a magnetron.

The electron beam lies within a region extending a distance h from the cathode, where h is known as the hub thickness. The spacing between the cathode and anode is d. The electron motion is assumed to be in the positive y direction with a velocity

$$\mathcal{V}_y = -\frac{E_x}{B_0} = \frac{1}{B_0}\frac{dV}{dx} \tag{10-1-44}$$

where $B_0 = B_z$ is the magnetic flux density in the positive z direction
V = potential

From the principle of energy conservation, we have

$$\tfrac{1}{2} m \mathcal{V}_y^2 = eV \tag{10-1-45}$$

Combining Eqs. (10-1-44) and (10-1-45) yields

$$\left(\frac{dV}{dx}\right)^2 = \frac{2eV}{m} B_0^2 \tag{10-1-46}$$

This differential equation may be rearranged as

$$\left(\frac{m}{2eB_0}\right)^{1/2} \frac{dV}{\sqrt{V}} = dx \tag{10-1-47}$$

Integration of Eq. (10-1-47) yields the potential within the electron beam as

$$V = \frac{eB_0^2}{2m} x^2 \tag{10-1-48}$$

where the constant of integration has been eliminated for $V = 0$ at $x = 0$.

The potential and electric field at the hub surface are given by

$$V(h) = \frac{e}{2m} B_0^2 h^2 \tag{10-1-49}$$

and

$$E_x = -\frac{dV}{dx} = -\frac{e}{m} B_0^2 h \tag{10-1-50}$$

The potential at the anode is thus obtained from Eq. (10-1-50) as

$$V_0 = -\int_0^d E_x\, dx = -\int_0^h E_x\, dx - \int_h^d E_x\, dx$$

$$= V(h) + \frac{e}{m} B_0^2 h(d - h)$$

$$= \frac{e}{m} B_0^2 h(d - h/2) \tag{10-1-51}$$

The electron velocity at the hub surface is obtained from Eqs. (10-1-44) and (10-1-50) as

$$\mathcal{V}_y(h) = \frac{e}{m} B_0 h \tag{10-1-52}$$

For synchronism, this electron velocity is equal to the phase velocity of the slow-wave structure. That is,

$$\frac{\omega}{\beta} = \frac{e}{m} B_0 h \tag{10-1-53}$$

For the π-mode operation, the anode potential is finally given by

$$V_{0h} = \frac{\omega B_0 d}{\beta} - \frac{m}{2e} \frac{\omega^2}{\beta^2} \tag{10-1-54}$$

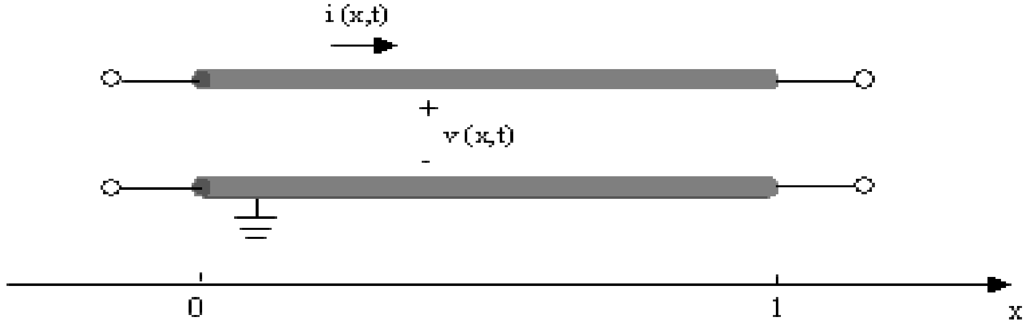
This is the Hartree anode voltage equation that is a function of the magnetic flux density and the spacing beween the cathode and anode.

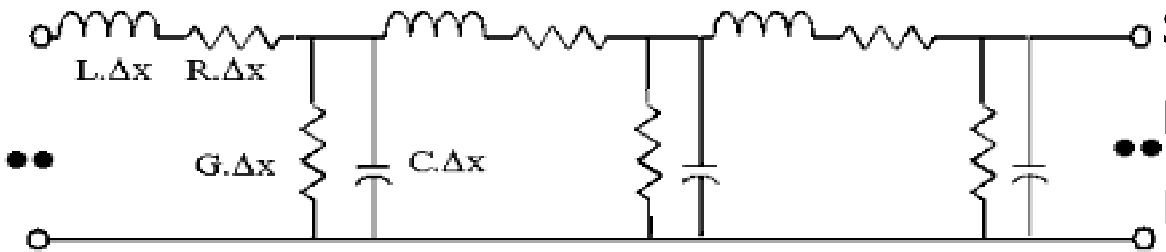
MICROWAVE MEASUREMENTS

3.1 Transmission line characteristics

<u>Transmission Line</u>- In the microwave frequency region, power is considered to be in electric and magnetic fields that are guided from place to place by some physical structure. Any physical structure that will guide an electromagnetic wave place to place.

<u>Transmission lines</u> are distributed devices. RLCG type models are commonly used to approximate the distributed behavior of a transmission line.





RLCG Model for Single Transmission Line

The single transmission line shown below can be modeled by a network consisting of a series resistance and inductance with parallel capacitance and conductance.

- **R Resistive** loss of the conductor (transmission line trace). Determined by the conductance of the metal, width, height, and length of the conductor.
- **L Inductive** part of the circuit resulting from the layout of the conductors.
- **C Capacitive** part of the circuit resulting from the layout of the conductors. Determined by the permittivity and thickness of the board material and the area of the conductor.
- **G Shunt** loss of the dielectric. Determined by the layout of the conductors, permittivity, loss tangent and thickness of the board material.

General Characteristics of Transmission Line

- Propagation delay per unit length (T_0) { time/distance} [ps/in] Or Velocity (v_0) {distance/ time} [in/ps]
- Characteristic Impedance (Z_0)
- Per-unit-length Capacitance (C_0) [pf/in]
- Per-unit-length Inductance (L_0) [nf/in]
- Per-unit-length (Series) Resistance (R_0) [W/in]
- Per-unit-length (Parallel) Conductance (G_0) [S/in]

Transmission Line Equations
Propagation equation

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

α is the attenuation (loss) factor
β is the phase (velocity) factor

Characteristic Impedance equation

$$Z0 = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}$$

Characteristics of transmission line

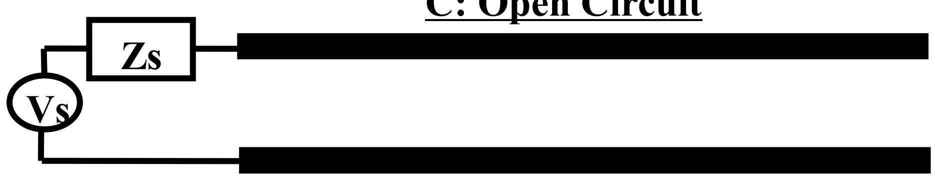
A: Terminated in Zo

$$\rho = \frac{Zo - Zo}{Zo + Zo} = 0$$

B: Short Circuit

$$\rho = \frac{0 - Zo}{0 + Zo} = -1$$

C: Open Circuit



$$P = \frac{\infty - Zo}{\infty + Zo} = 1$$

The Reflection and Transmission Losses

- When the resistive load termination is not equal to the characteristic impedance, part of the power is reflected back and the remainder is absorbed by the load
- . The amount of voltage reflected back is called *voltage reflection coefficient.*

$$\Gamma = V_i/V_r$$

where Vi is incident voltage and vr is reflected voltage.

The reflection coefficient is also given by :

$$\Gamma = (Z_L - Z_O)/(Z_L + Z_O)$$

VOLTAGE STANDING WAVE RATIO (VSWR)

- A standing wave is formed by the addition of incident and reflected waves and has nodal points that remain stationary with time.

- *Voltage Standing Wave Ratio:*

$$\mathbf{VSWR = V_{max}/V_{min}}$$

Voltage standing wave ratio expressed in decibels;

SWR (dB) =
$20\log_{10}VSWR$

- The maximum impedance of the line is given by:
- $Z_{max} = V_{max}/I_{min}$

- The minimum impedance of the line is given by:
- $Z_{min} = V_{min}/I_{max}$

or alternatively:

- $Z_{min} = Z_o/VSWR$

- Relationship between VSWR and Reflection Coefficient:

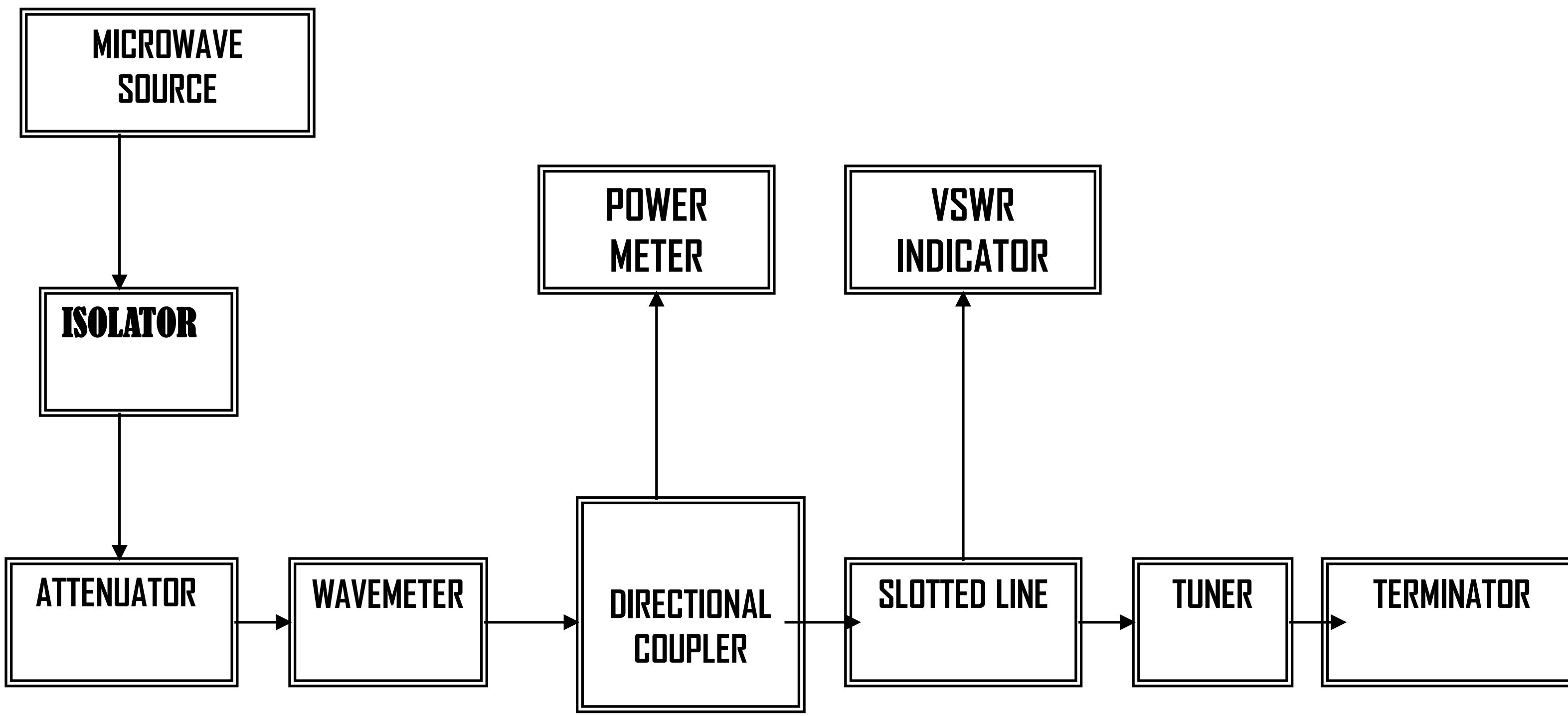
$$\mathbf{VSWR = (1 + |\ \Gamma\ |)/(1 - |\ \Gamma\ |)}$$

$$\mathbf{\Gamma = (VSWR - 1)/(VSWR + 1)}$$

TYPES OF MEASUREMENT

TYPES OF MEASUREMENT	EQUIPMENTS
FREQUENCY-DOMAIN	➢ Wavemeter s (absorption, transmission or reaction). ➢ Slotted lines. ➢ Spectrum analyzer, frequency sweepers and frequency counters.
DISPLAY OF TIME-DOMAIN	➢ Sampling oscilloscope. ➢ Oscilloscope.
VSWR	➢ Slotted lines (direct method or double minimum method)
POWER	➢ Power meters. ➢ Detectors with oscilloscopes. ➢ Spectrum analyzers.
WAVELENGTH	➢ Coaxial and waveguide slotted lines
NOISE	➢ Noise meters.
	➢ Network analyzer – multifunctional test equipment.

BLOCK DIAGRAM OF INSTRUMENT IN MICROWAVE TESTING.



FUNCTION OF EACH BLOCK

MICROWAVE SOURCE – generates microwave source in X-band (8 – 12 GHz);

e.g klystron, magnetron or TWT

ISOLATOR /CIRCULATOR - Allow wave to travel through in one direction while being attenuated in the other direction or it is use to eliminate the unwanted generator frequency pulling (*changing the frequency of the generator*) due to system mismatch or discontinuity. (*to prevent reflected energy from reaching the source*)

- **ATTENUATOR** - Control the amount of power level in a fixed amount, variable amount or in a series of fixed steps from the from the microwave source to the wavemeter.
- **WAVEMETER** - Used to select / measure resonant cavity frequencies by having a plunger move in and out of the cavity thus causes the the cavity to resonate at different frequencies.
- **DIRECTIONAL COUPLER** - Samples part of the power travelling through the main waveguide and allows part of its energy to feed to a secondary output port. Ideally it is used to separate the incident and reflected wave in a transmission line.
- **SLOTTED LINE -** Used to determine the field strength through the use of a detector probe that slides along the top of the waveguide.

- **VSWR INDICATOR -** Denotes the value of VSWR measured by the slotted line.

- **TUNER -** Allows only the desired frequency to appear at the output. Any harmonic frequencies that appear at the output are reduced to an acceptable level.

- **TERMINATOR -** May range from a simple resistive termination to some sort of deep-space antenna array, active repeater or similar devices. 3 special cases of transmission line i.e short circuit, open circuit, match impedance.

FREQUENCY MEASUREMENT

- The frequency meter used has a cavity which is coupled to the waveguide by a small coupling hole which is used to absorb only a tiny fraction of energy passing along the waveguide.

- Adjusting the micrometer of the Frequency Meter will vary the plunger into the cavity. This will alters the cavity size and hence the resonance frequency.

- The readings on the micrometer scales are calibrated against frequency. As the plunger enters the caviy, its sized is reduced and the frequency increases.

- The wavemeter is adjusted for maximum or minimum power meter readings depending on whether the cavity is a transmission or absorption type device. With the transmission-type device, the power meter will be adjusted for a maximum. It only allows frequency close to resonance to be transmitted through them. Other frequencies are reflected down the waveguide. The wavemeter acts as a short circuit for all other frequencies.

- For the absorption-type wavemeter, the power meter will be adjusted for a minimum. Its absorp power from the line around resonant frequency and act as a short to other frequencies.

- The absorbing material used is to absorb any unwanted signal that will cause disturbance to the system.

VSWR (VOLTAGE STANDING WAVE RATIO) MEASUREMENT

- Used to determine the degree of mismatch between the source and load when the value VSWR ≠ 1.
- Can be measured by using a slotted line. **Direct Method Measurement** is used for VSWR values upto about 10. Its value can be read directly using a standing wave detector .
- The measurement consists simply of adjusting attenuator to give an adequate reading, making sure that the frequency is correct and then using the dc voltmeter to measure the detector output at a maximum on the slotted section and then at the nearest minimum.

The ratio of the voltage maximum to the minimum gives the VSWR i.e

$$VSWR = V_{max} / V_{min}$$

$$ISWR = I_{max} / I_{min}$$

$$= k(V_{max})^2 / k(V_{min})^2$$

$$= (V_{max} / V_{min})^2$$

$$= VSWR^2$$

$$\boxed{VSWR = \sqrt{(I_{max} / I_{min})} = \sqrt{ISWR}}$$

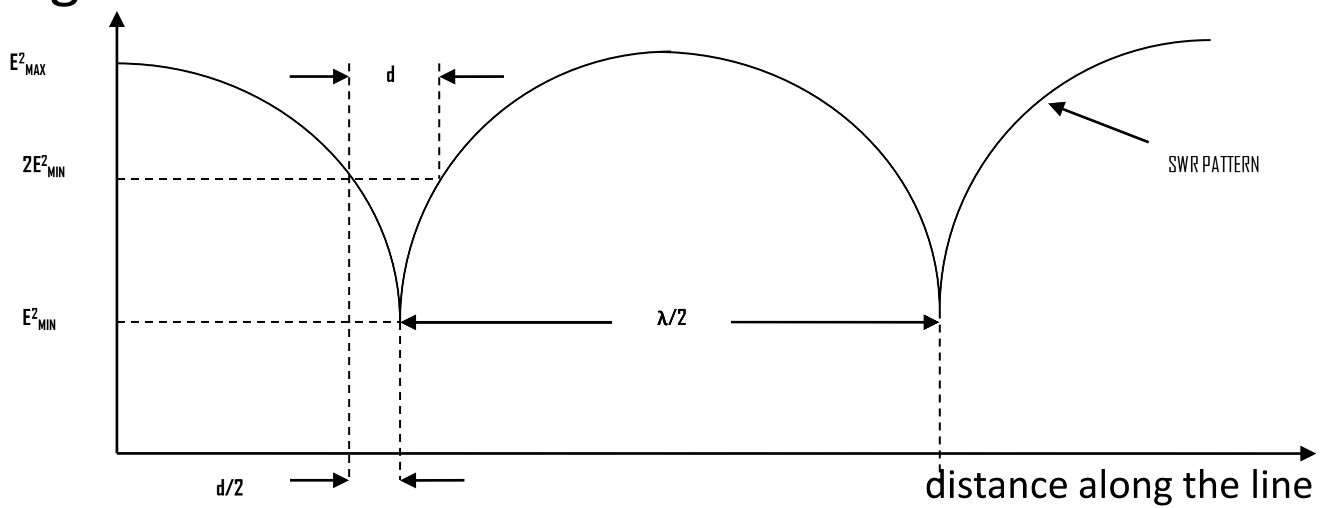
- Methods used depends on the value of VSWR whether it is high or low. If the load is not exactly matched to the line, standing wave pattern is produced.

- Reflections can be measured in terms of voltage, current or power. Measurement using voltage is preffered because it is simplicity.

- When reflection occured, the incident and the reflected waves will reinforce each other in some places, and in others they will tend to cancel each other out.

DOUBLE MINIMUM METHOD MEASUREMENT (VSWR > 10)

- 'Double Minimum' method is usually employed for VSWR values greater than about 10.



- The detector output (proportional to field strength squared) is plotted against position. The probe is moved aling the line to find the minimum value of signal.

- It is then moved either side to determine 2 positions at which twice as much detector signal is obtained. The distance d between these two positions then gives the VSWR according to the formula :

$$\mathbf{S = \sqrt{1 + 1/Sin^2(\pi d/\lambda)}}$$

POWER MEASUREMENT

- Power is defined as the quantity of energy dissipated or stored per unit time.
- Methods of measurement of power depend on the frequency of operation, levels of power and whether the power is continuous or pulsed.
- The range of microwave power is divided into three categories :-

  i. Low power (< 10mW @ 0dBm)

  ii. Medium power (from 10 mW - 10 W @ 0 – 40 dBm)

  iii. High power (> 10 W @ 40 dBm)

- The microwave power meter consists of a power sensor, which converts the microwave power to heat energy.
- The sensors used for power measurements are the Schottky barrier diode, bolometer and the thermocouple.

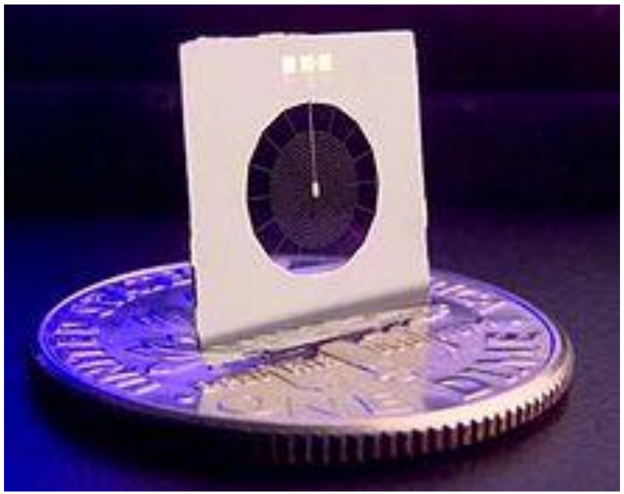
SCHOTTKY BARRIER DIODE

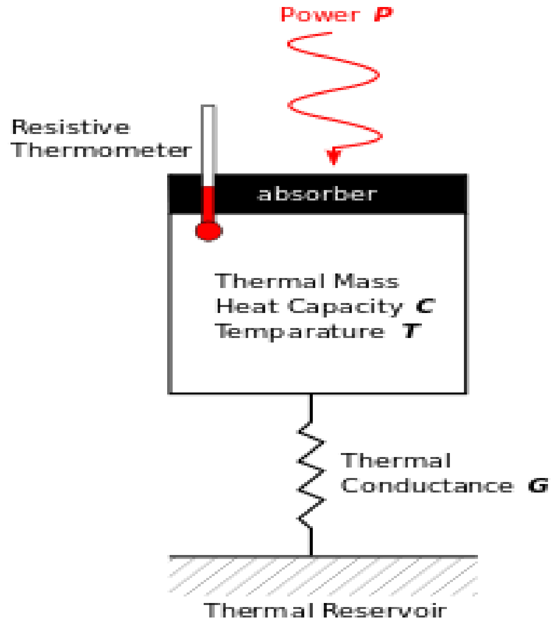
- A zero-biased Schottky Barrier Diode is used as a square-law detector whose output is proportional to the input power.
- The diode detectors can be used to measure power levels as low as 70dBm.

BOLOMETERS

- A Bolometer is a power sensor whose resistance changes with temperature as it absorbs microwave power.
- Are power detectors that operate on thermal principles. Since the temperature of the resistance is dependent on the signal power absorbed, the resistance must also be in proportion to the signal power.
- The two most common types of bolometer are, the barretter and the thermistor. Both are sensitive power detectors and is used to indicate microwatts of power. They are used with bridge circuits to convert resistance to power using a meter or other indicating devices.

BOLOMETER




Power P
Resistive
Thermometer
absorber
Thermal Mass
Heat Capacity C
Temparature T
Thermal
Conductance G
Thermal Reservoir

BARETTERS

- Are usually thin pieces of wire such as platinum. They are mounted as terminating devices in a section of transmission line. The section of transmission line with the mounting structure is called a detector mount.
- The increase of temperature of the baretter due to the power absorbed from the signal in the line causes the temperature of the device to increase.
- The temperature coefficient of the device causes the resistance to change in value in proportion to the change in temperature of the device (positive temperature coefficient i.e the resistance increases with increasing temperature; $R \alpha \; t$).

BARETTER


LGC
LGC
J1
J2
MODEL 2677
0.1-20 GHz SWITCH
S/N
GENERAL ®
MICROWAVE
08415-60057
MADE IN ISRAEL
J3-COM

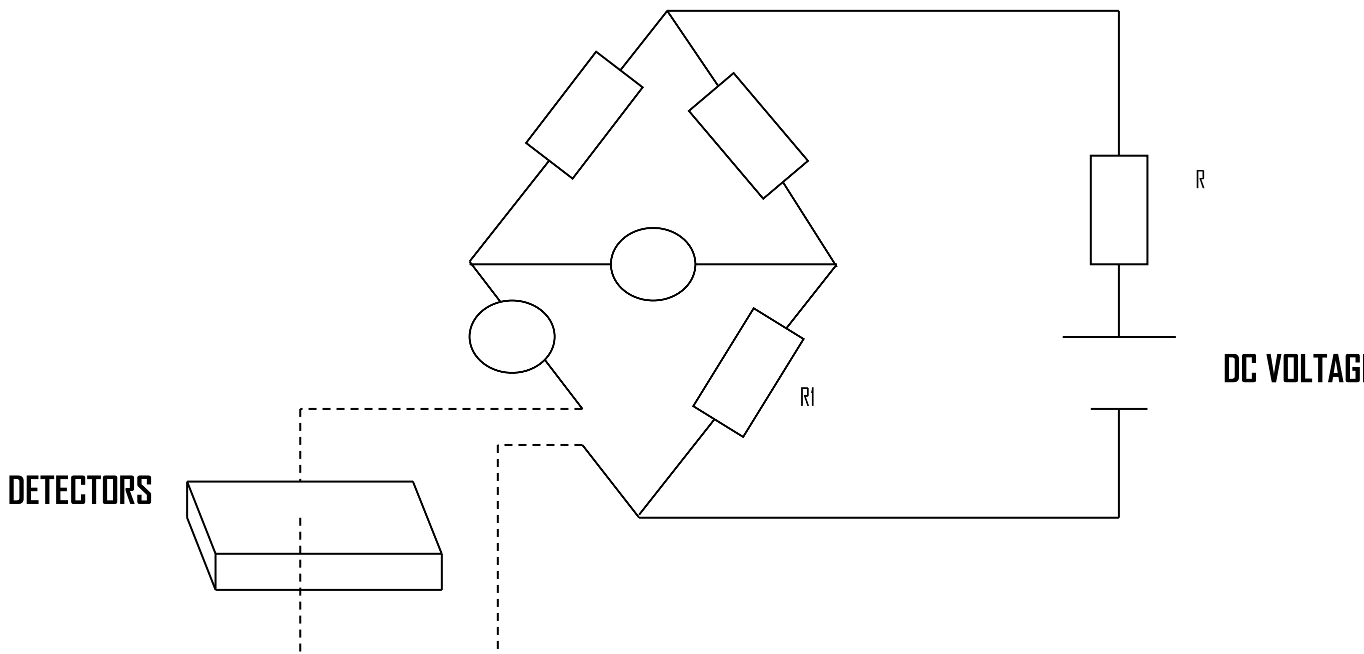
THERMISTOR

- Are beads of semiconductor material that are mounted across the line. They have a negative temperature coefficient i.e the resistance decreases with increasing temperature; $R \propto 1/t$.

- The impedance of baretters and thermistors must match that of the transmission so that all power is absorbed by the device.

Thermistor mount

- Variations in resistance due to thermal-sensing devices must be converted to a reading on an indicating device such as a meter. This can be done accurately using a balanced bridge arrangement as shown below:-



- With no power to the detector that contains the sensor element, the sensor-line R1 is adjusted to zero reading through the meter M1 and the bridge circuit is balanced.

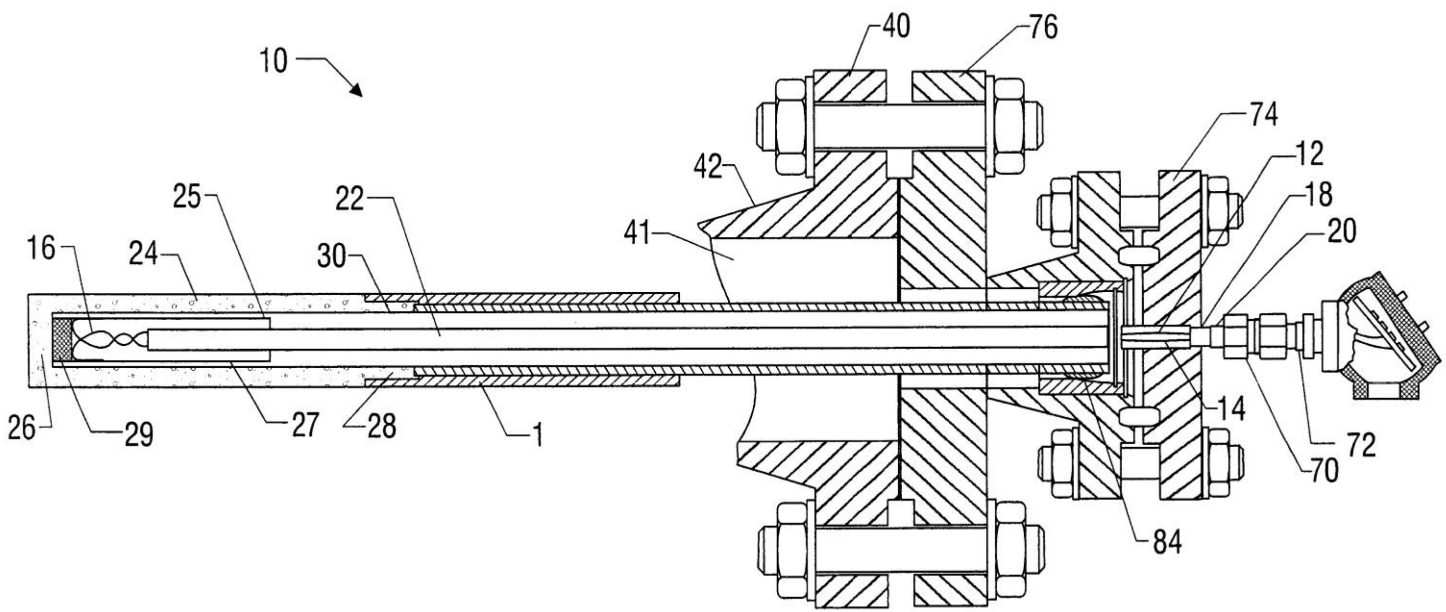
- When signal is applied to the sensor element, causing its temperature to change, the sensor resistance changes, causing the bridge to become unbalanced.

- Resistor R1 is adjusted to balance meter M1. The change in the reading of meter M2 in the sensor element leg is a direct measure of the microwave power.

THERMOCOUPLES

- Are used as power monitors in the low-to-medium power regions and are very sensitve.
- Is a thin wire made of two disimilar metals. Hence there will be two junctions (hot & cold).
- When the temperature at two junctions are different, a voltage is developed across the thermocouple (i.e across both junctions). This developed voltage is proportional to the difference between the two junction temperatures.
- When the temperature at both junctions are the same, the difference in voltage = 0.

Thermocouple



MICROWAVE CRYSTALS

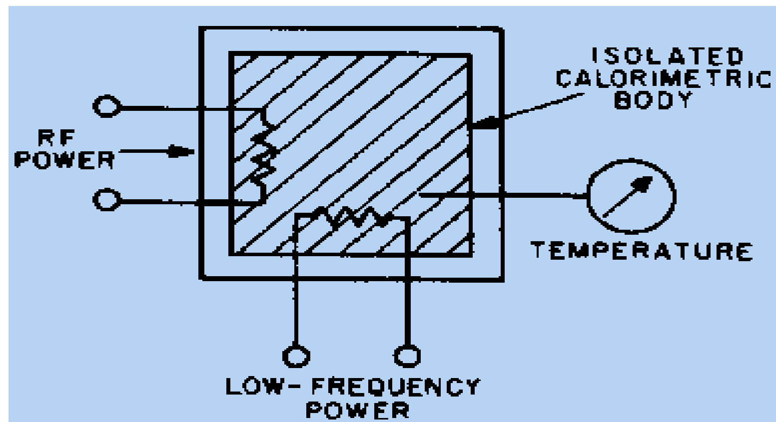
- Are non-linear detectors that provide current in proportion to the power. It is limited to making low-power measurements.
- The current is proportional to the power due to the square-law characteristic of the crystal. This square-law characteristic only occurs for small signal levels.
- At larger signal levels the relationship is linear, as with any diode. Therefore the proportional relationship between power and current output is only true at power levels below 10mW.

Microwave Crystal

CALORIMETERS

- The calorimeters are the most accurate of all instruments for measuring high power. Calorimeters depend on the complete conversion of the input electromagnetic energy into heat. Direct heating requires the measurement of the heating effect on the medium, or load, terminating the line. Indirect heating requires the measurement of the heating effect on a medium or body other than the original power-absorbing material. Power measurement with true calorimeter methods is based solely on temperature, mass, and time. *Substitution* methods use a known, low-frequency power to produce the same physical effect as an unknown of power being measured. Calorimeters are

CALORIMETER



THANK YOU