Microwave Engineering

(EC0505)

Unit-4

B.Tech. (Electronics and Communication)

Semester-V

Asst. Prof. Zalak Patel

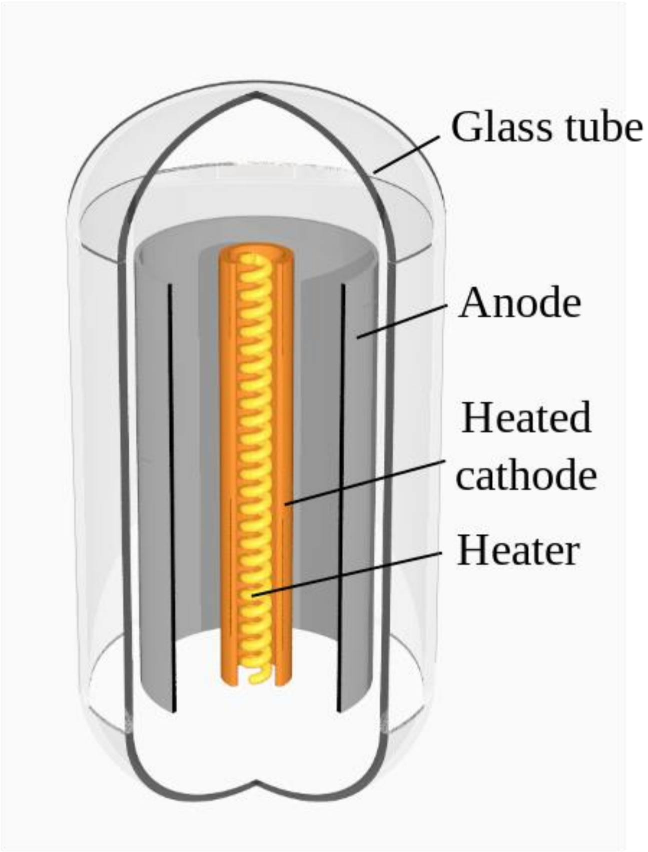
Academic Year 2019-2020

Microwave tubes and circuits

- Klystron Oscillator
- Reflex Klystron
- Traveling Wave Tube
- Magnetron

Conventional tube

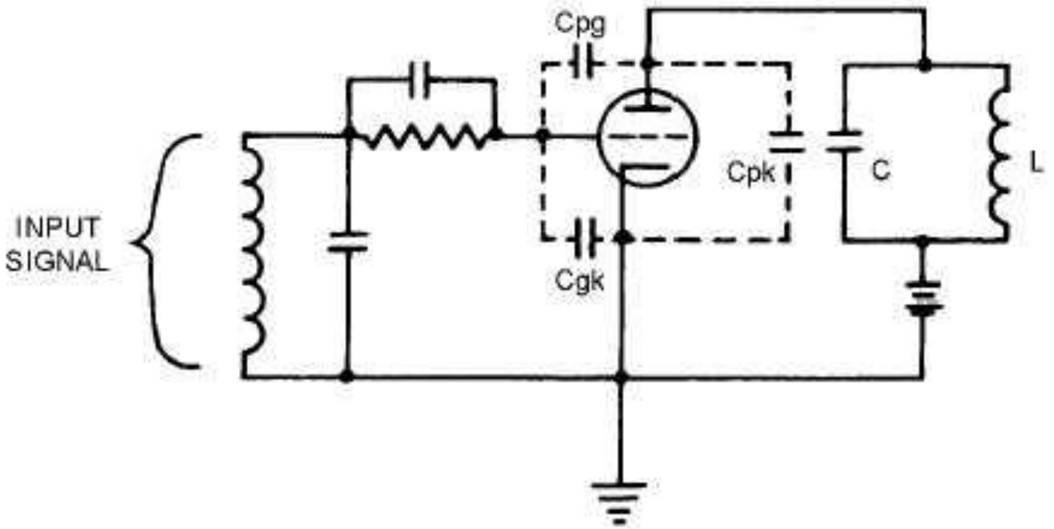
- The earliest vacuum tubes evolved from incandescent light bulbs, containing a filament sealed in an evacuated glass envelope.
- When hot, the filament releases electrons into the vacuum
- A second electrode, the anode or *plate*, will attract those electrons if it is at a more positive voltage. The result is a net flow of electrons from the filament to plate.



- However, electrons cannot flow in the reverse direction because the plate is not heated and does not emit electrons.

- The filament (*cathode*) has a dual function: it emits electrons when heated; and, together with the plate, it creates an electric field due to the potential difference between them. Such a tube with only two electrodes is termed a diode, and is used for rectification..

High frequency Limitation of conventional tube



➢The INTERELECTRODE CAPACITANCE between the grid and the cathode (Cgk) in parallel with the signal source. As the frequency of the input signal increases, the effective grid-to-cathode impedance of the tube decreases because of a decrease in the reactance of the interelectrode capacitance.($X_C=1/2\pi fc$)

➢ If the signal frequency is 100megahertz or greater, the reactance of the grid-to-cathode capacitance is so small that much of the signal is short-circuited within the tube.

- Another frequency-limiting factor is the LEAD INDUCTANCE of the tube elements. Since the lead inductances within a tube are effectively in parallel with the inter electrode capacitance, the net effect is to raise the frequency limit.

- However, the inductance of the cathode lead is common to both the grid and plate circuits.

- This provides a path for degenerative feedback which reduces overall circuit efficiency.

- A third limitation caused by tube construction is TRANSIT TIME. Transit time is the time required for electrons to travel from the cathode to the plate.

- While some small amount of transit time is required for electrons to travel from the cathode to the plate, the time is insignificant at low frequencies.

- However, at high frequencies, transit time becomes an appreciable portion of a signal cycle and begins to hinder efficiency.

- If the tube is to operate efficiently, the plate current must be in phase with the grid-signal voltage and 180 degrees out of phase with the plate voltage.

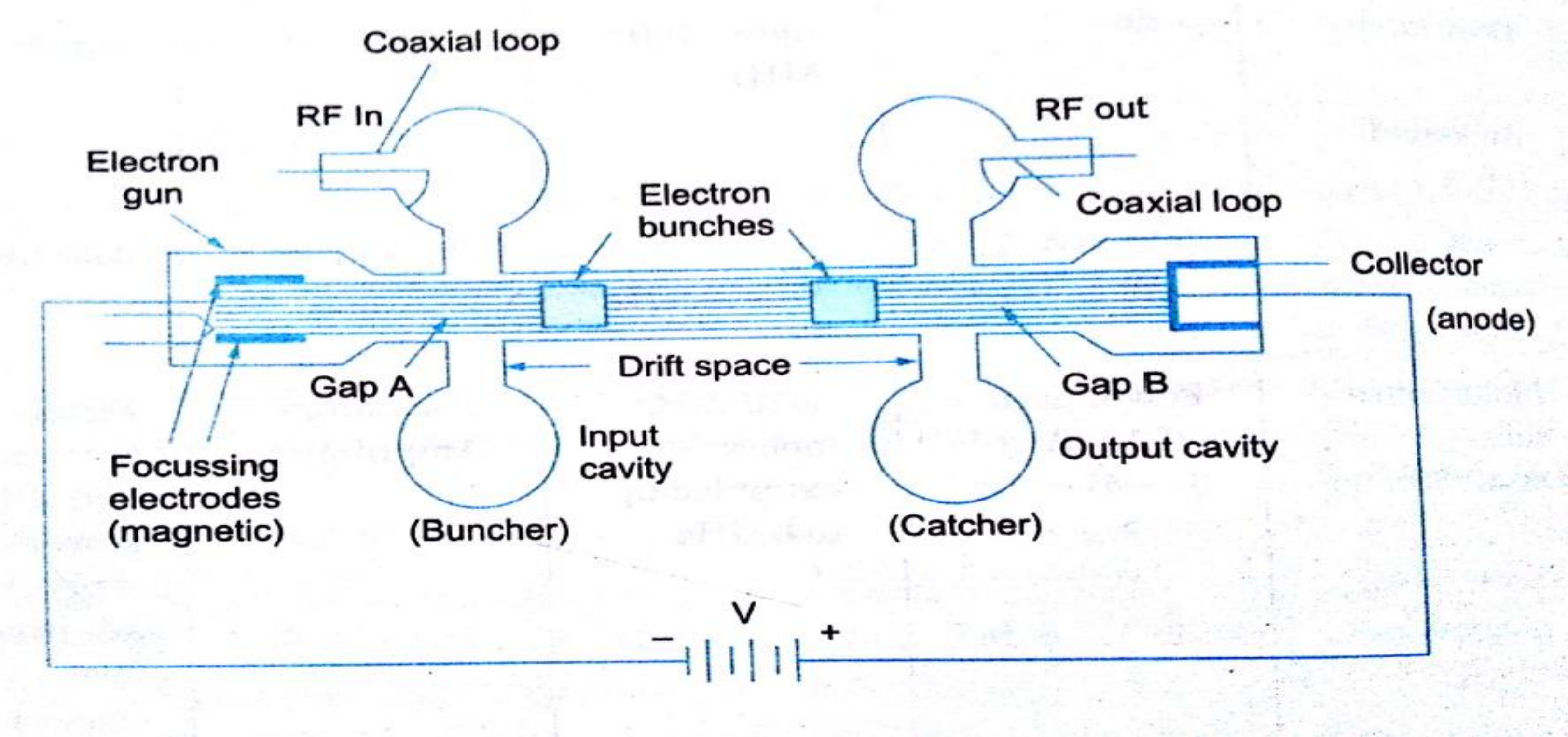
- When transit time approaches 1/4 cycle, this phase relationship between the elements does not hold true. A positive swing of a high-frequency grid signal causes electrons to leave the cathode and flow to the plate. Initially this current is in phase with the grid voltage.

- However, since transit time is an appreciable part of a cycle, the current arriving at the plate now lags the grid-signal voltage. As a result, the power output of the tube decreases and the plate power dissipation increases. Another loss of power occurs because of **ELECTROSTATIC INDUCTION.**

Klystron Amplifier

- A klystron is a vacuum tube that can be used as an amplifier of power, at microwave frequencies.

- It works on the principle of interaction between electron and RF field of a cavity resonator.



Construction of Klystron Amplifier

- An electron gun consists of a Cathode, tungsten filament to heat the cathode, an anode and focusing beam electrodes.

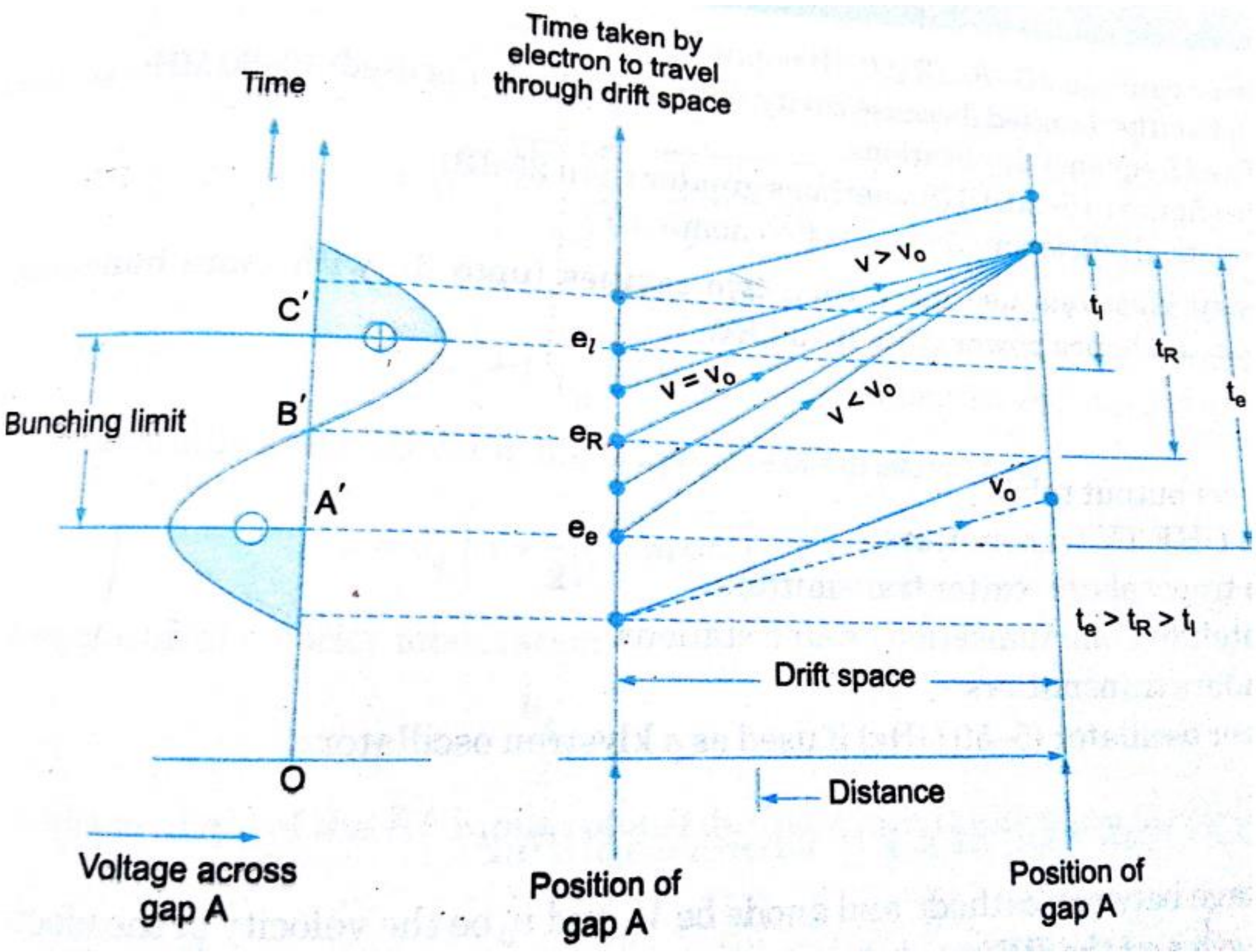
- Anode is kept at +ve potential & accelerates the electrons emitted by cathode and they are later collected by collector.

- It uses reentrant cavities in which EM power can be coupled into or out of it through a coupling loop arrangement shown in figure.

- The microwave/RF input is given to buncher cavity and output being obtained from catcher cavity by means of a coaxial line. .

Operation of Klystron Amplifier

- E field component in the cavity is colinear with the electron beam axis.
- Hence electrons passing through Gap A see an accelerating field for half a cycle and retarding field for other half a cycle.
-
- Therefore, some electrons will be accelerated and some will be retarded depending on the its interaction with RF field.
- That is called **velocity modulation of electrons which causes the bunching of electrons.**



Time
Time taken by electron to travel through drift space
v > v0
C′
e_l
t_l
t_R
t_e
v = v0
v < v0
Bunching limit
B′
e_R
A′
v0
e_e
t_e > t_R > t_l
Drift space
O
Distance
Voltage across gap A
Position of gap A
Position of gap A

- Electrons entering the grid Gap A at time instant B’ will experience zero RF field and travels without any change in its initial velocity.

- Electrons entering the grid Gap A at time instant A’ will move slower because of its interaction with -ve/retarding RF field.

- Electrons entering the grid Gap A at time instant B’ will move faster because of its interaction with +ve/accelerating RF field.

- As a result of **these differences in velocities, electrons tend to cluster at some point in drift space. (bunching process)**

- The location of bunches depends on the initial velocity of electrons, RF field amplitude and its time period.

- **As density of electrons in beam vary periodically with time, it is called current modulation.**

- second cavity, called a CATCHER CAVITY, must be placed at a point of maximum bunching to take useful energy from the beam.

- The electron bunches will induce an rf voltage in the grid gap B of the second cavity causing it to oscillate.

- Proper placement of the second cavity will cause the induced grid-gap voltage to decelerate the electron bunches as they arrive at the gap.

- Since the largest concentration of electrons is in the bunches, slowing the bunches causes a transfer of energy to the output cavity.

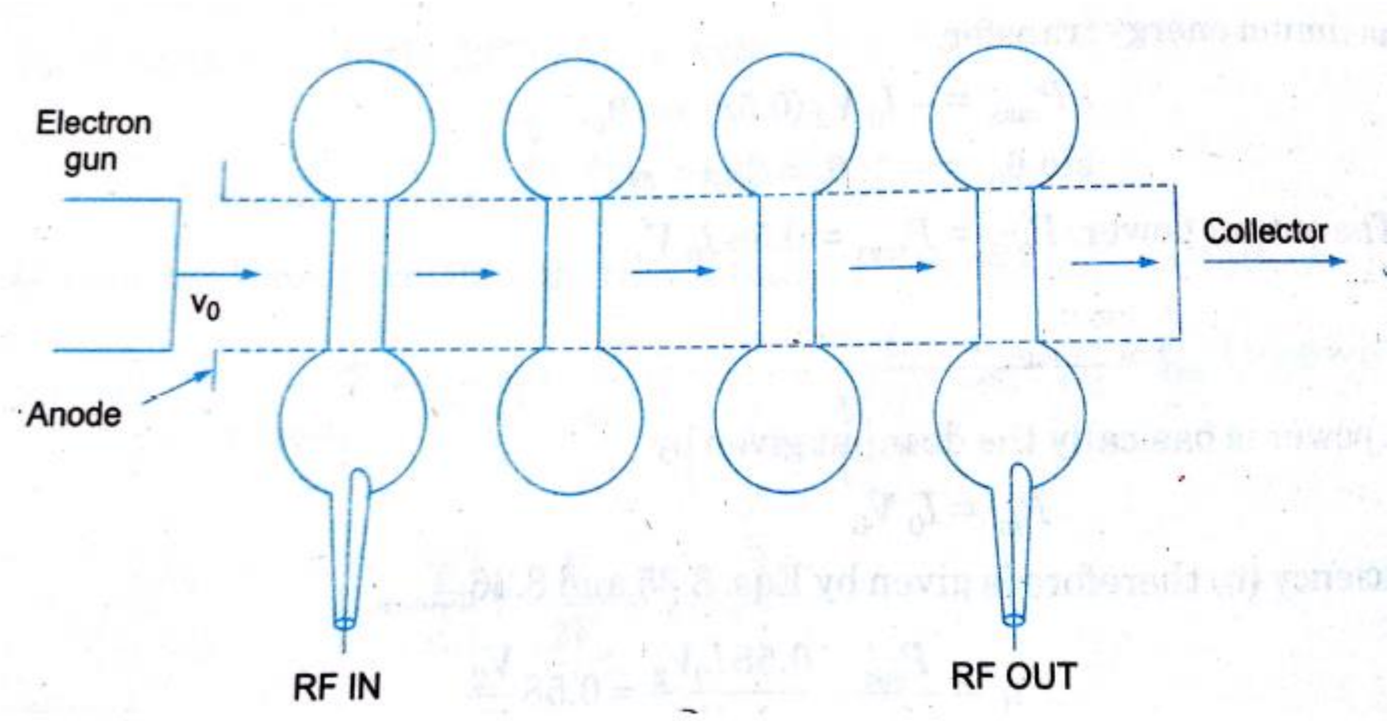
- Therefore, if the second cavity is properly positioned, useful energy can be transferred from a velocity modulated electron beam to the RF field in second cavity.

- **Little RF power applied to the buncher cavity results in large beam current pulses being applied to catcher cavity and with considerable power gain as a result.**

Applications

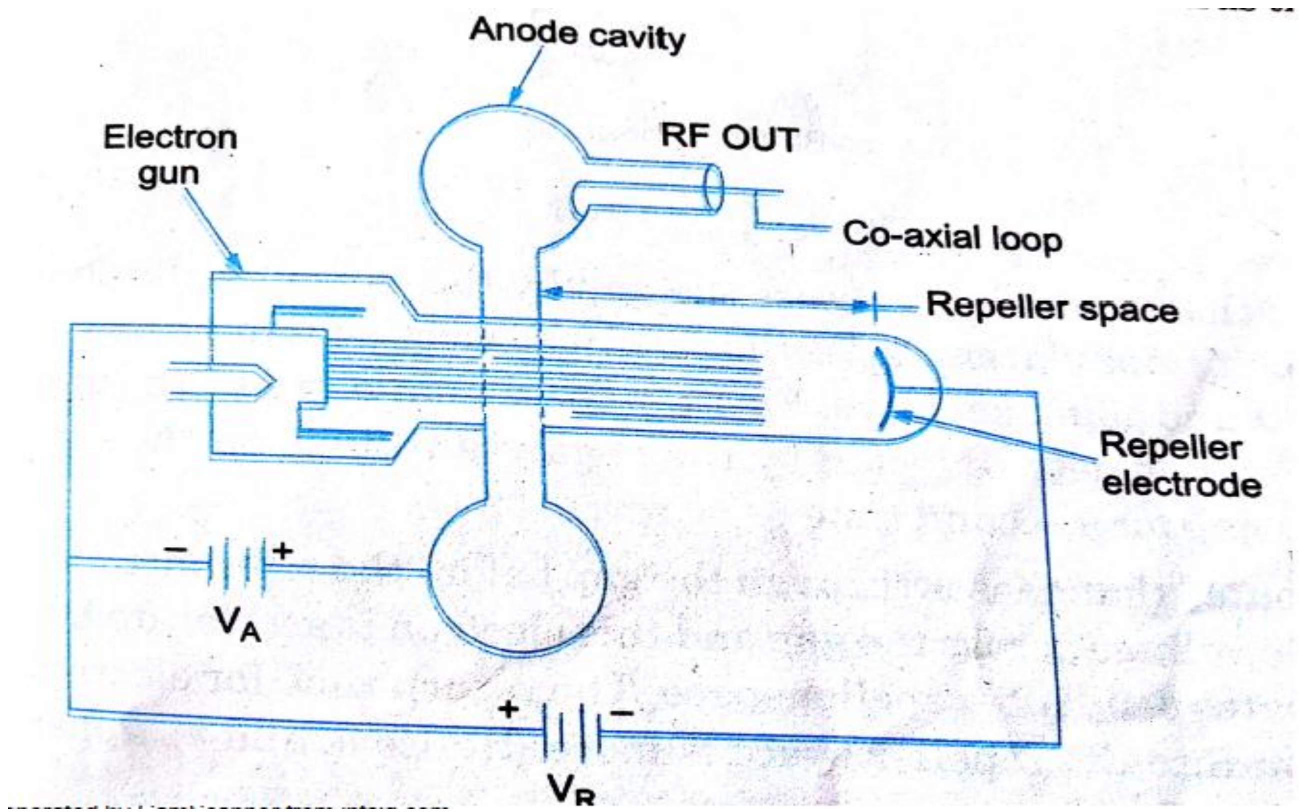
- **As power output tubes**
  1. in UHF TV transmitters
  2. in troposphere scatter transmitters
  3. satellite communication ground station
  4. radar transmitters

Multi cavity Klystron



Reflex Klystrons

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



Construction

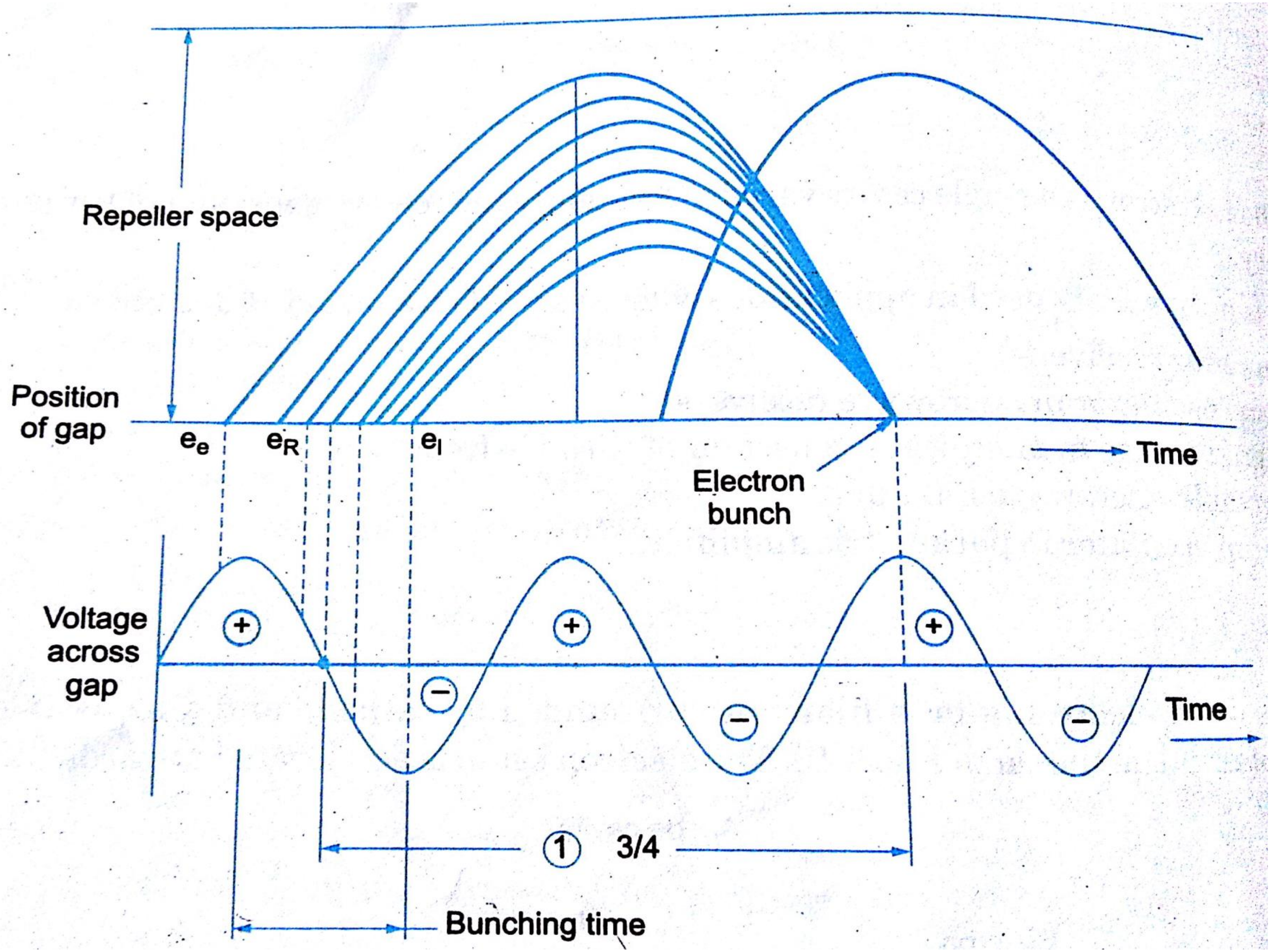
- A reflex klystron consists of an **electron gun, a cavity with a pair of grids and a repeller plate** as shown in the above diagram.
- In this Reflex klystron, a single pair of grids does the functions of both the buncher and the catcher grids.
- The main difference between two cavity klystron amplifier 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 catcher now, therby the same pair of grids acting simultaneously as a buncher for the forward moving electrons and as a catcher for the returning beam.

Bunching in Reflex Klystrons

- The Bunching phenomenon can be visualized by studying the electron trajectories in the region between cavity & repeller **(Repeller Space)**.
- An electron $\mathbf{e_R}$ which passes through a resonator gap when RF voltage across the gap is zero. So it travels with steady initial velocity and being repelled by the repeller returns to the cavity resonator.
- Another electron $\mathbf{e_e}$ passes through the gap Δt time earlier than $\mathbf{e_R}$, interacts with +ve RF voltage across the gap, hence it travels with speed higher than initial velocity and travel further toward the repeller and take long time to come back to cavity resonator.
- Similarly, electron $\mathbf{e_L}$ passes through the gap Δt time later than $\mathbf{e_R}$, interacts with –ve RF voltage and slows down and takes less time to come back to cavity resonator.



Repeller space
Position of gap
e_e
e_R
e_l
Time
Electron bunch
Voltage across gap
+
−
Time
1 3/4
Bunching time

Bunching in Reflex Klystrons

- If the repeller voltage is set at the correct value, the electrons will form a bunch around the constant-speed electrons.
- The electrons will then return to the grid gap at the instant the RF field is at the correct polarity to cause maximum deceleration of the bunch.
- Thus slowing the bunches causes a transfer of energy to the same cathcer cavity.
- The constant-speed electrons must remain in the repeller space for a minimum time of ¾ Time Period of the grid RF field for maximum energy transfer. Which will produce the oscillations in resonator cavity.

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

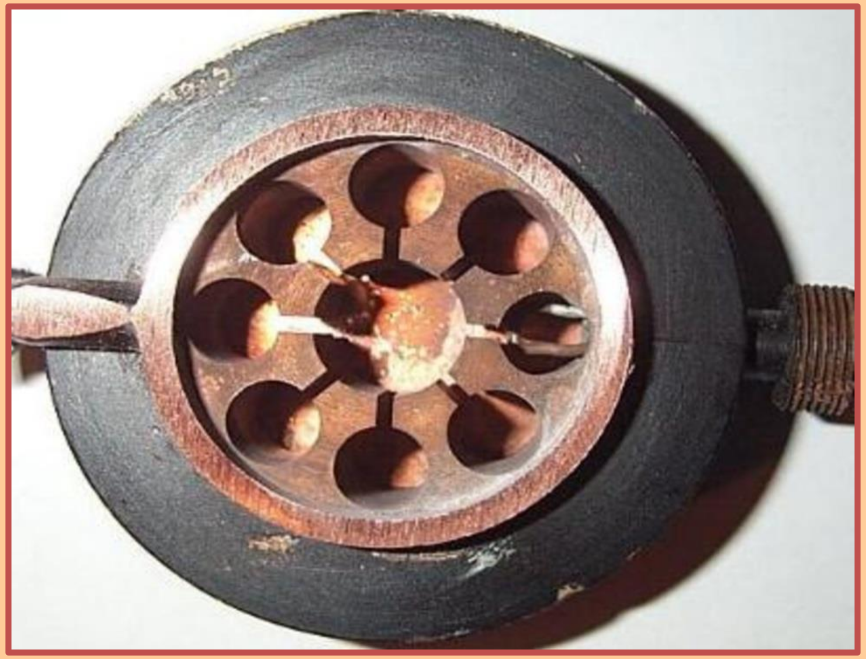
Applications

- 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

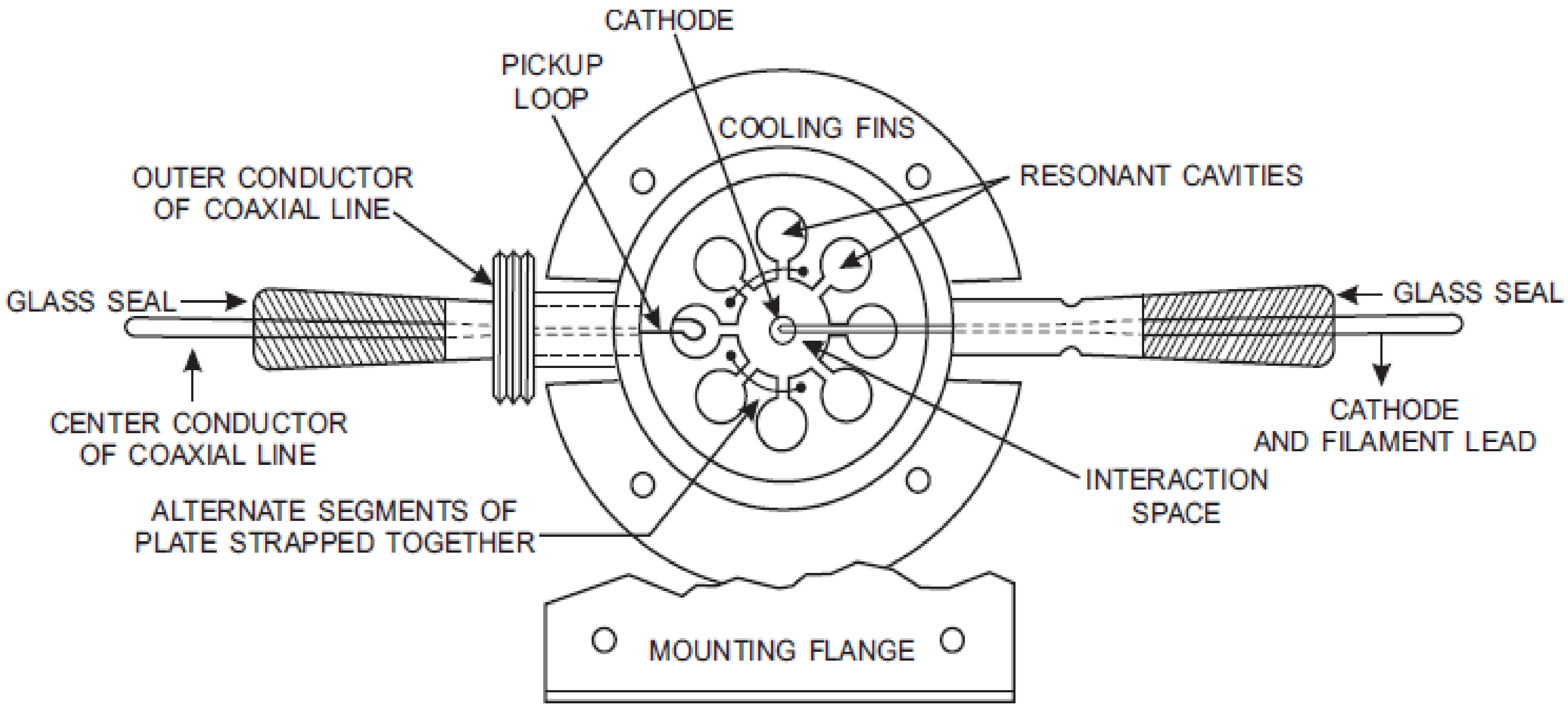
Magnetron oscillator

- Magnetrons provide microwave oscillations of very high frequency.



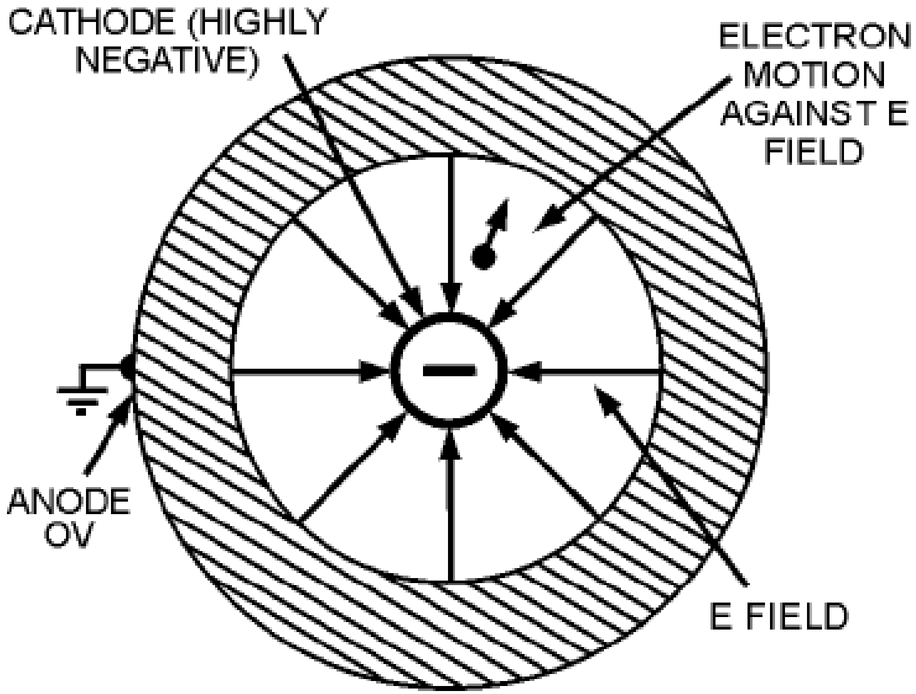
Magnetron

- **CROSSED-ELECTRIC and MAGNETIC fields** are used in the magnetron (cylindrical diode) to produce the high-power output required in radar and communications equipment.
- The cathode and filament are at the center of the tube and are supported by the filament leads.
- The output lead is usually a co-axial probe or loop extending into one of the tuned cavities and coupled into a waveguide or coaxial line.
- The plate structure, shown in figure is a solid block of copper.
- The cylindrical holes around its circumference are resonant cavities (anode).
- It is a cylindrical plate with a cathode placed along the center axis of the plate.


CATHODE
PICKUP
LOOP
COOLING FINS
OUTER CONDUCTOR
OF COAXIAL LINE
RESONANT CAVITIES
GLASS SEAL
GLASS SEAL
CENTER CONDUCTOR
OF COAXIAL LINE
CATHODE
AND FILAMENT LEAD
INTERACTION
SPACE
ALTERNATE SEGMENTS OF
PLATE STRAPPED TOGETHER
MOUNTING FLANGE

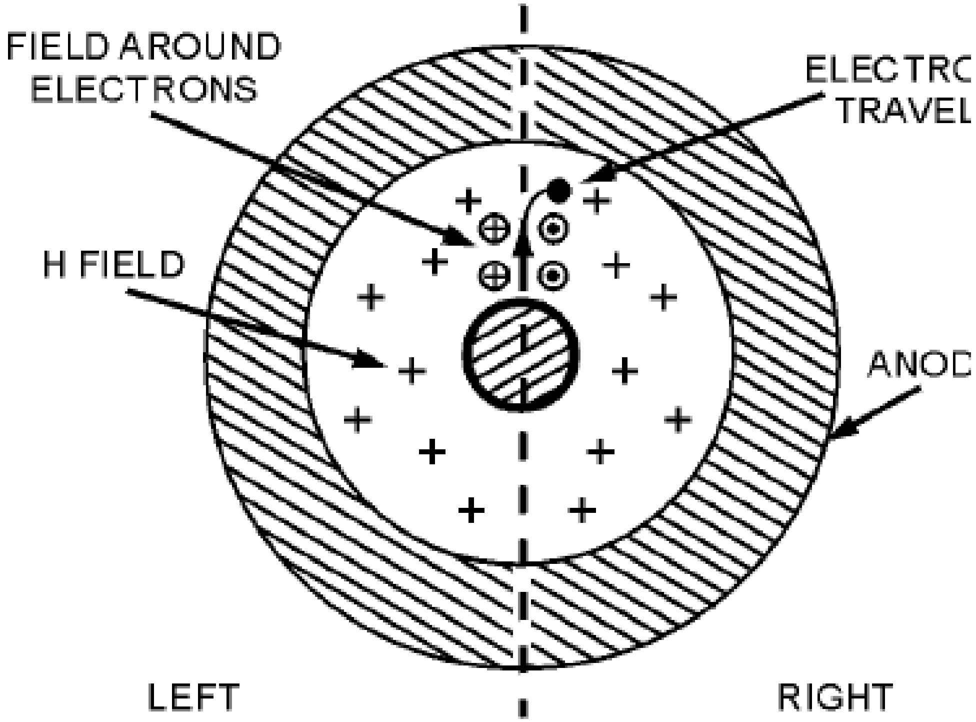
- A narrow slot runs from each cavity into the central portion of the tube dividing the inner structure into as many segments as there are cavities.
- The open space between the plate and the cathode is called the INTERACTION SPACE. In this space the electric and magnetic fields interact to electrons.
- The magnetic field is usually provided by a strong, permanent magnet mounted around the magnetron so that the magnetic field is parallel with the axis of the cathode exert force upon the electrons.
- The cathode is mounted in the center of the interaction space.

- **BASIC MAGNETRON OPERATION :**
- Magnetron theory of operation is based **on the motion of electrons under the influence of combined electric and magnetic fields.**
- The force exerted by an electric field on an electron is proportional to the strength of the field. Electrons tend to move from a point of negative potential toward a positive potential.
- In other words, electrons tend to move against the E field.
- When an electron is being accelerated by an E field, as shown in figure , energy is taken from the field by the electron.



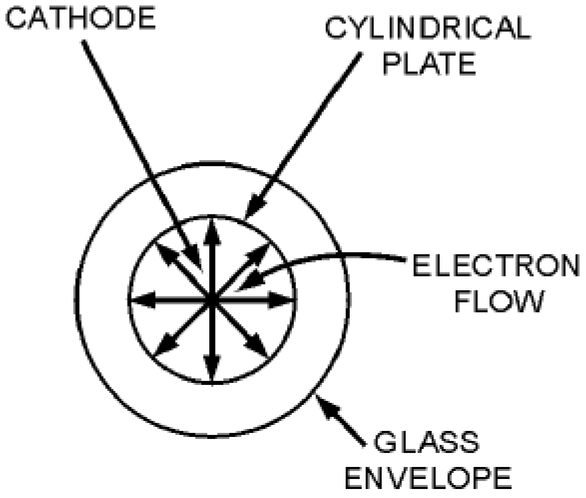
- **The law of motion of an electron in a magnetic field (H field) states:** The force exerted on an electron in a magnetic field is at right angles to both the field and the path of the electron.

$$\overline{F} = -e(\overline{v} \times \overline{B})$$



- In figure it is assume that a south pole is below the figure and a north pole is above the figure so that the magnetic field is going into the paper.
- When an electron is moving through space, a magnetic field builds around the electron just as it would around a wire when electrons are flowing through a wire.

- The magnetic field around the moving electron **adds** to the permanent magnetic field on the left side of the electron's path and **subtracts** from the permanent magnetic field on the right side.
- This action weakens the field on the right side; therefore, the electron path bends to the right (clockwise).
- If the strength of the magnetic field is increased, the path of the electron will have a sharper bend. Likewise, if the velocity of the electron increases, the field around it increases and the path will bend more sharply.


CATHODE
CYLINDRICAL PLATE
ELECTRON FLOW
GLASS ENVELOPE

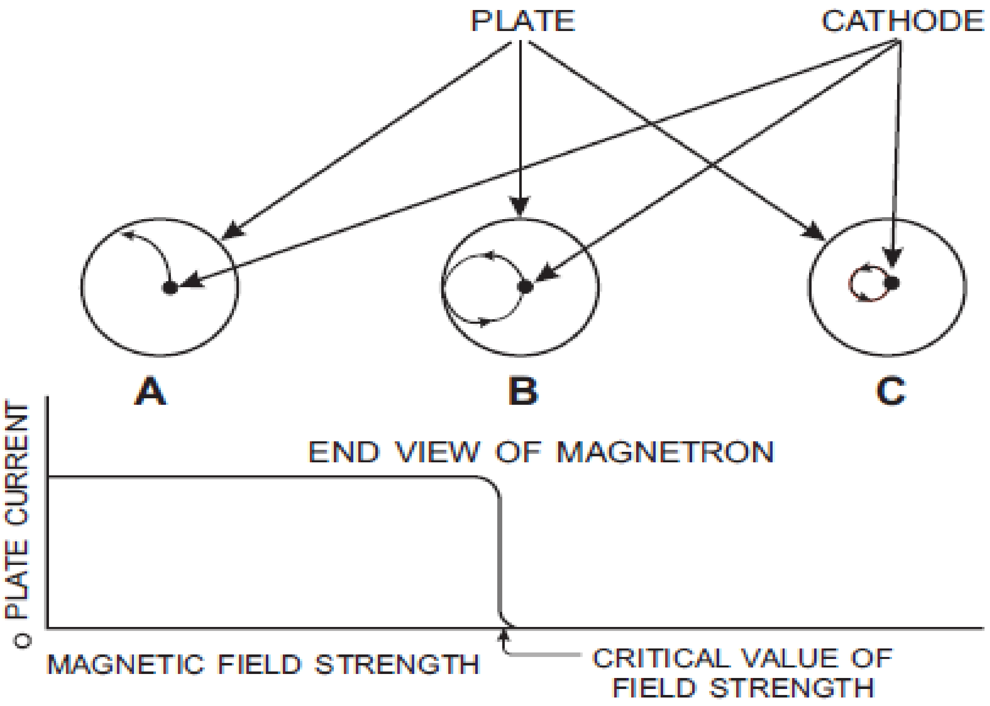


PLATE
CATHODE
A
B
C
END VIEW OF MAGNETRON
PLATE CURRENT
O
MAGNETIC FIELD STRENGTH
CRITICAL VALUE OF FIELD STRENGTH

- When no magnetic field exists, heating the cathode results in a uniform and direct movement of the field from the cathode to the plate.
- However, as the magnetic field surrounding the tube is increased, a single electron is affected, where the electron proceeds to the plate in a curve rather than a direct path.
- In view (B) of figure , the magnetic field has reached a value great enough to cause the electron to just miss the plate and return to the filament in a circular orbit. This value is the CRITICAL VALUE of field strength.
- In view (C), the value of the field strength has been increased to a point beyond the critical value; the electron is made to travel to the cathode in a circular path of smaller diameter.

- Also how the magnetron plate current varies under the influence of the varying magnetic field is shown in last figure.
- In view (A), the electron flow reaches the plate, so a large amount of plate current is flowing. However, when the critical field value is reached, as shown in view (B), the electrons are deflected away from the plate and the plate current then drops quickly to a very small value. When the field strength is made still greater, as shown in view (C), the plate current drops to zero.
- When the magnetron is adjusted to the cutoff, or critical value of the plate current, and the electrons just fail to reach the plate in their circular motion, it can produce oscillations at microwave frequencies. These oscillations are caused by the currents induced electrostatically by the moving electrons.
- The frequency is determined by the time it takes the electrons to travel from the cathode toward the plate and back again.

- A transfer of microwave energy to a load is made possible by connecting an external circuit between the cathode and the plate of the magnetron.

Performance Characteristics

1. Power output: In excess of 250 kW (Pulsed Mode), 10 mW (UHF band), 2 mW (X band), 8 kW (at 95 GHz)
2. Frequency: 500 MHz – 12 GHz
3. Duty cycle: 0.1 %
4. Efficiency: 40 % - 70 %

Applications of Magnetron

1. Pulsed radar is the single most important application with large pulse powers.
2. Voltage tunable magnetrons are used in sweep oscillators in telemetry and in missile applications.
3. Fixed frequency, CW magnetrons are used for industrial heating and microwave ovens.

Comparison of TWTA and Klystron Amplifier

Klystron Amplifier	TWTA
1. Linear beam or 'O' type Device	1. Linear beam or 'O' type device
2. Uses Resonant cavities for input and output circuits	2. Uses non resonant wave circuits
3. Narrowband device	3.Wideband device

Traveling Wave Tube

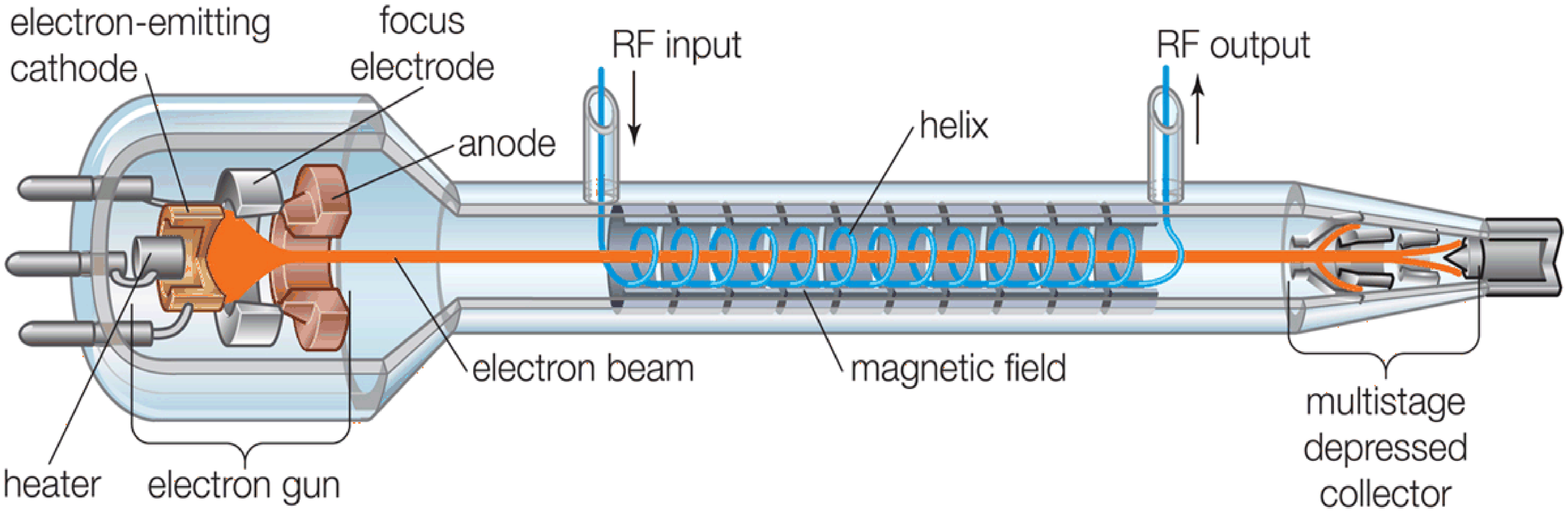
➢Traveling Wave Tube (TWT) is the most versatile microwave RF power amplifiers.

➢The main virtue of the TWT is its extremely wide band width of operation. **(Broad band device)**

- **Longitudinal static magnetic field applied (e-beam focusing)**
- **Interaction into Slow Wave Structures (SWS)**
- **The electron velocity modulation creates bunches**
- **The electron kinetic energy is converted into RF-Energy**

- In order to prolong interaction between the electron beam and RF field , both must move in same direction with same velocity.
- In previous, electron beam travels but the RF field is stationary at gap of cavity resonator.
- RF field travels with the speed of light while electron beam velocity is very slow compare to it even with high anode voltage.
- So to retard the RF field with slow wave structure. (Helix configuration)

Basic structure of a Traveling Wave Tube (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. (to provide prolong interaction)
- 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 centre 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 .

- The speed of RF field is given by velocity of light multiplied by the ratio of helix pitch to helix circumference.

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 RF voltages into the helix which reinforce the RF 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.

- Amplification begins as the electron bunches form and release energy to the RF signal on the helix. The slightly amplified signal causes a denser electron bunch which, in turn, amplifies the signal even more.

- The amplification process is continuous as the rf wave and the electron beam travel down the length of the tube.

- 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.

Why attenuator is needed?

- An attenuator is placed over a part of the helix on midway to attenuate any reflected waves generated due to the impedance mismatch.

- It is placed after sufficient length of the interaction region so that the attenuation of the amplified signal is insignificant compared to the amplification.

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 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)

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.