23EC701:MICROWAVE AND OPTICAL COMMUNICATIONS

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UNIT-I

Microwave Tubes

Microwave Tubes: Limitations and Losses of conventional Tubes at Microwave Frequencies, Microwave Tubes – O Type and M Type Classifications, O-type Tubes: 2 Cavity Klystrons – Structure, Reentrant Cavities, Velocity Modulation Process and Applegate Diagram, Bunching Process and Small Signal Theory – Expressions for O/P Power and Efficiency. Reflex Klystrons – Structure, Velocity Modulation and Applegate Diagram, Mathematical Theory of Bunching, Power Output, Efficiency, Oscillating Modes and O/P Characteristics.

Helix TWTs: Types and Characteristics of Slow Wave Structures; Structure of TWT and Amplification Process (qualitative treatment), Suppression of Oscillations, Gain Considerations.

Introduction

- At microwave frequencies, the size of electronic devices required for generation of microwave energy becomes smaller and smaller.
- Smaller devices results in lesser power handling capability and increased noise levels.
- So, at microwave frequencies, the microwave tubes are used because they can provide higher output powers, lesser noise, better reliability with reduced output power levels.
- Conventional triodes, tetrodes and pentodes are used at low microwave frequencies.
- Special tubes would be required at UHF frequencies as conventional tubes have certain limitations

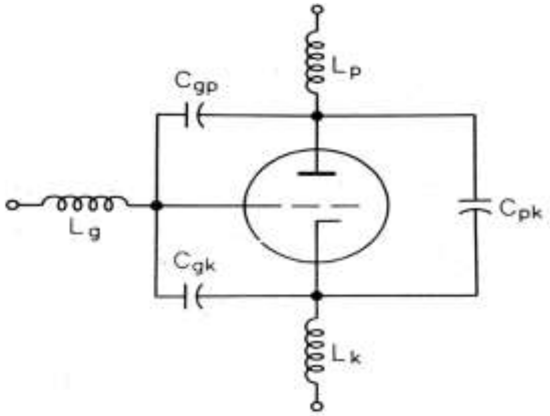
Limitations of Conventional Tubes

Because of the following effects conventional devices cannot be used for frequencies greater than 100MHz.

- Inter electrode capacitance effect
- Lead inductance effect
- Transit time effect
- Gain bandwidth limitation
- Effects due to RF losses (Conductance/Skin depth or I^2R losses and the dielectric losses)
- Effect due to radiation losses

Inter Electrode Capacitance (IEC) Effect

- As the frequency increases, the reactance $X_c = 1/2\,\pi f C$ decreases and the output voltage decreases.



- Because at higher frequencies X_c becomes almost short.
- C_{gp}, C_{gk} and C_{pk} are the IEC's which come into effect.
- The effect of IEC can be minimised by reducing the IEC's C_{gp}, C_{gk} and C_{pk}.
- These can be reduced by decreasing the area of the electrodes (since $C = \varepsilon_0 \varepsilon_r\, A/D$) or by increasing the distance between electrodes.

Lead Inducatance Effect

- As the frequency increases, the reactance $X_L = 2\pi f L$ increases and hence the voltages appearing at the active electrodes are less than the voltages at the base pins.
- This results in reduced gain for the tube amplifier.
- L_k, L_p and L_g are the lead inductances that limit the performance of the tube.
- The effect of LI can be minimised by decreasing L, since L is proportional to reactance (L= $l/\mu_0\mu_r A$)
- L can be decreased by using larger sized short leads without base pins i.e., by increasing 'A' and by decreasing 'l'
- However reduces the power handling capability.

Transit Time Effect

- Transit time is the time taken for the electron to travel from cathode to anode.

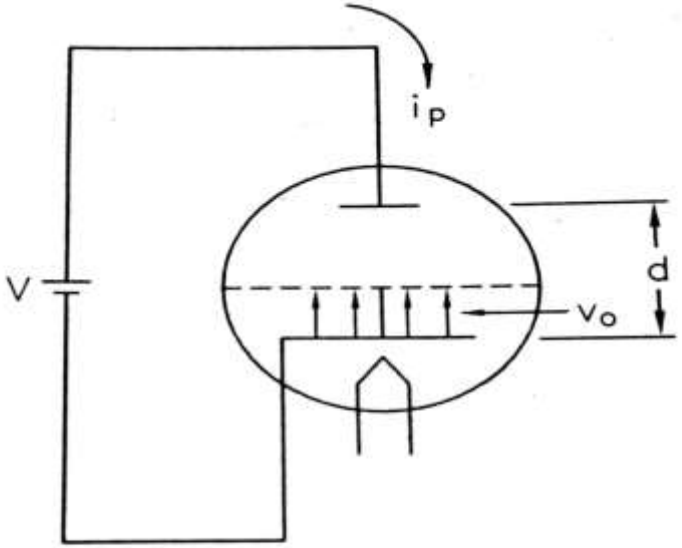
Transit time = $\tau = \dfrac{d}{v_0}$

d = distance between anode and cathode

v_0= velocity of electrons

Static energy of electrons=eV

Under equilibrium, Static energy=Kinetic energy



Transit Time Effect

- At low frequencies, the transit time effect is negligible because the distance between the anode and cathode is very small.
- At high frequencies the transit time is large as compared with the period of the signal which is very small—nano seconds as shown in below fig.

- The grid potential during negative half cycle thus removes energy that was given to the electron during the positive half cycle.
- The overall result of the transit time effects is to reduce the overall efficiency of the vacuum tube.

Transit Time Effect

Remedy for Transit Time Effect:

To minimize transit time ($\tau = d/\sqrt{2eV/m}$), the separation between electrode can be decreased (but this increase the IEC) and the plate to cathode potential 'V' can be increased (This can not be increased indefinitely).

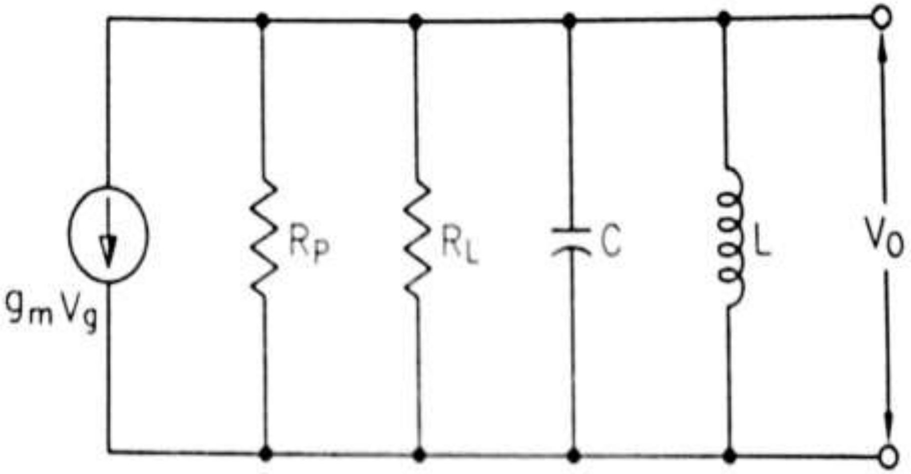
Therefore a trade off between IEC and transit time is must.

Gain Bandwidth Limitation

Maximum gain is achieved when the tuned circuit is at resonance.

Transfer function

$$\text{Gain } G = \frac{V_o(s)}{V_i(s)} = Z_o(s)$$



Applying Laplace transform to the parallel circuit

and replacing R_L and R_P by $R = \frac{1}{R_L} + \frac{1}{R_P}$,

$$\frac{1}{Z_o(s)} = Y_o(s) = Cs + \frac{1}{Ls} + \frac{1}{R} = \frac{s^2LCR + Ls + R}{RLs}$$

$$Z_o(s) = \frac{s/C}{s^2 + \frac{s}{CR} + \frac{1}{LC}}$$

Gain Bandwidth Limitation

- The roots of the characteristic equation (denominator) give the frequencies

$$\omega_1 = -\frac{G}{2C} - \sqrt{\left(\frac{G}{2C}\right)^2 - \frac{1}{LC}}$$

$$\omega_2 = -\frac{G}{2C} + \sqrt{\left(\frac{G}{2C}\right)^2 - \frac{1}{LC}}$$

where $G = \frac{1}{R}$.

Bandwidth, $BW = \omega_2 - \omega_1 = \frac{G}{C}$ for $\left(\frac{G}{2C}\right)^2 \gg \frac{1}{LC}$.

The maximum gain at resonance is $A_{max} = gm/G$.

$\therefore$ Gain bandwidth product $= A_{max} \cdot BW = \frac{gm}{G} \times \frac{G}{C} = \frac{gm}{C}$.

The gain bandwidth product is thus independent of frequency. Higher gain for a given tube can be achieved only by using the narrow band width.

In microwave circuits the gain bandwidth limitation can be overcome by use of

- Re entrant cavities
- Slow wave tubes

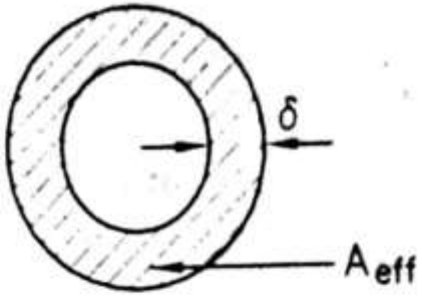
Effect Due To RF Losses

a) Skin effect losses (or Conductor or I^2R losses):

These losses come into play at higher frequencies at which the current has the tendency to confine itself to a smaller cross section of the conductor towards its outer surface.

$$\delta = \text{skin depth} = \sqrt{2/\omega\mu\sigma}$$

$$\delta \propto \frac{1}{\sqrt{\omega}} \text{ and } \delta \,\alpha\, A_{eff},$$



is the effective area over which current flows

$$A_{eff} \propto 1/\sqrt{f}$$

$$R = \frac{\rho l}{A_{eff}}$$

$$R = \frac{\rho l}{1/\sqrt{f}} = \rho l \sqrt{f}$$

Effect Due To RF Losses

b) Dielectric losses:

- This occurs in various types of insulting materials used in the device i.e., spacers, glass envelope, silicon or plastic encapsulations etc.
- The loss in any of these materials is in general given by

$$P = \pi f \cdot V_o^2 \, \varepsilon_r \tan \sigma$$

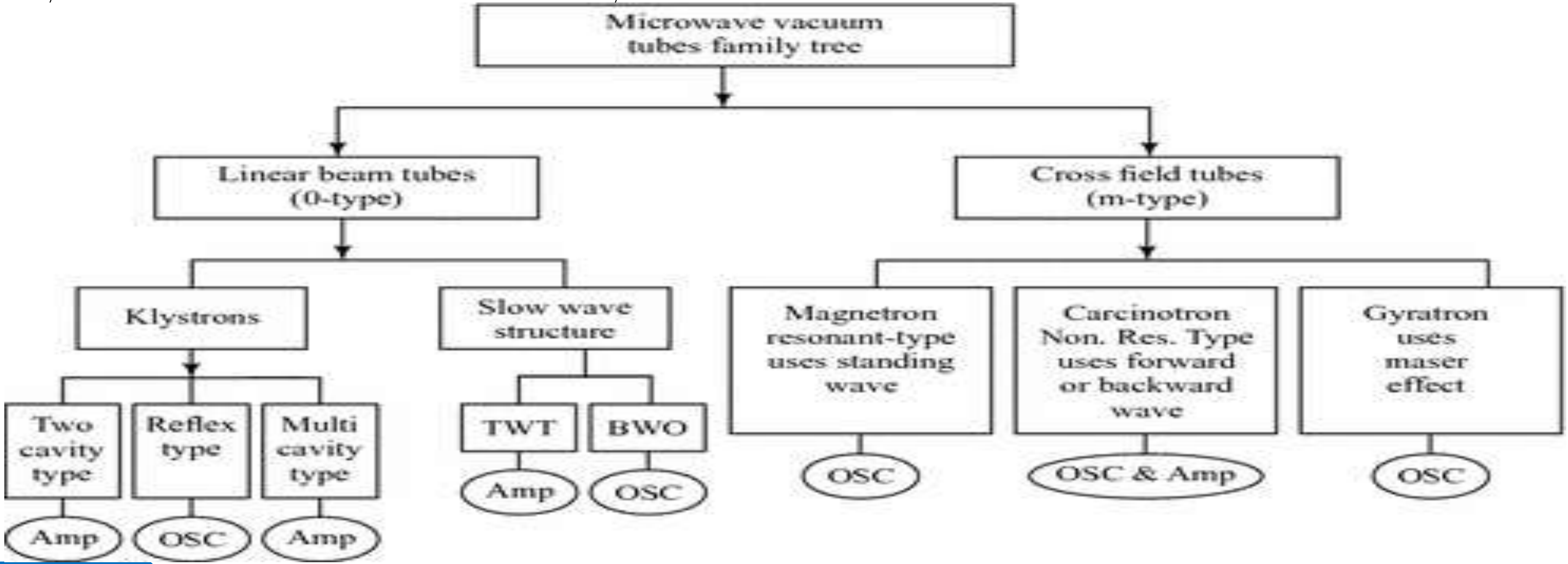
- As f increases the power loss increases.
- The solution for this is to eliminate the tube base and to reduce the surface area of glass.

Radiation Losses

- Whenever the dimensions of the wire approaches the wavelength, it will emit radiation.
- i.e., radiation losses increase with increase in frequency.
- The remedy for this is to use proper shielding of the tubes and its circuitry.

Microwave Tubes

- The basic principle of operation of the microwave tubes involves transfer of power from a source of dc voltage to a source of ac voltage by means of a current density modulated electron beam.

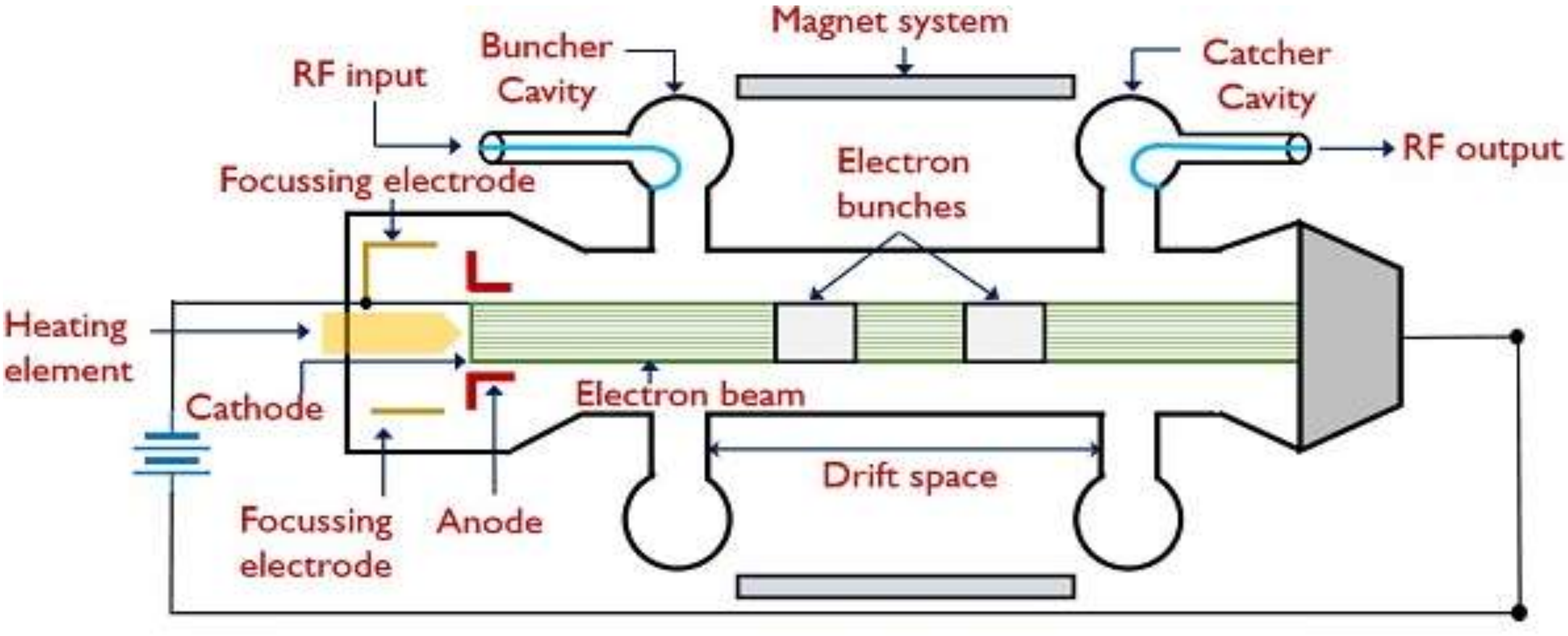


Klystrons

- A klystron is a vacuum tube that can be used either as a generator or as an amplifier at microwave frequencies.
- Invented by Russel H Varian & S.P Varian at Stanford University in 1939
- Types of Klystrons are
  - Two cavity Klystron Amplifier
  - Multicavity Klystron
  - Two Cavity Klystron Oscillator
  - Reflex Klystron

Two Cavity Klystron Amplifier

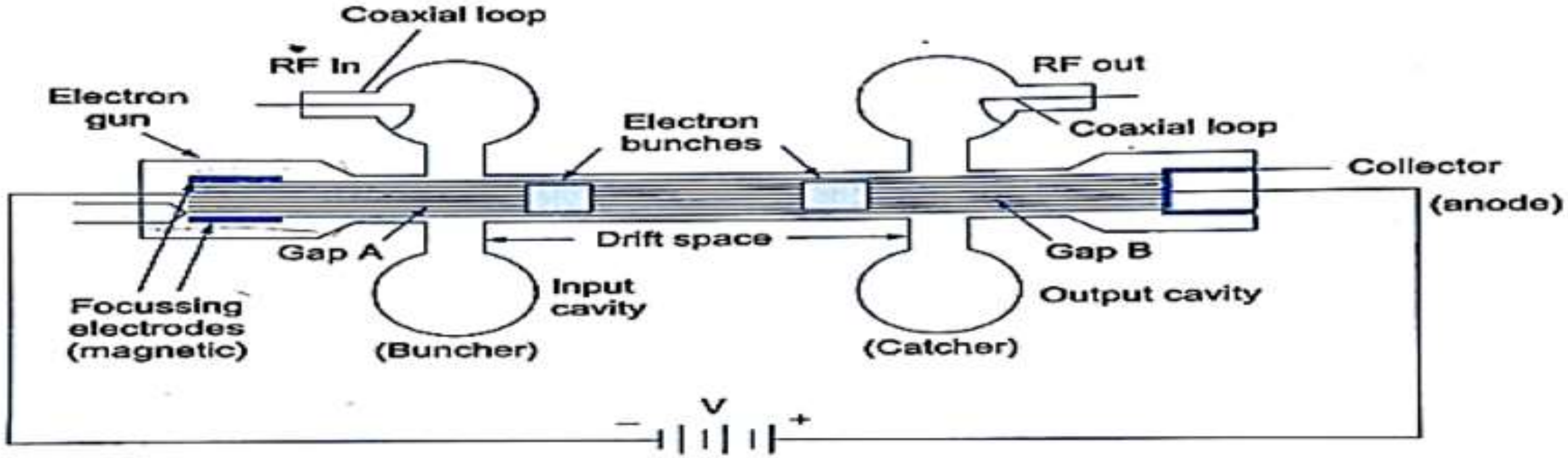
- Two cavity klystron amplifier shown here is basically a velocity modulated tube.



Two Cavity Klystron Amplifier

- Here a high velocity electron beam is formed and sent down along a glass tube through the input cavity (Buncher), a field free drift space and an output cavity (catcher) to a collector electrode/anode.

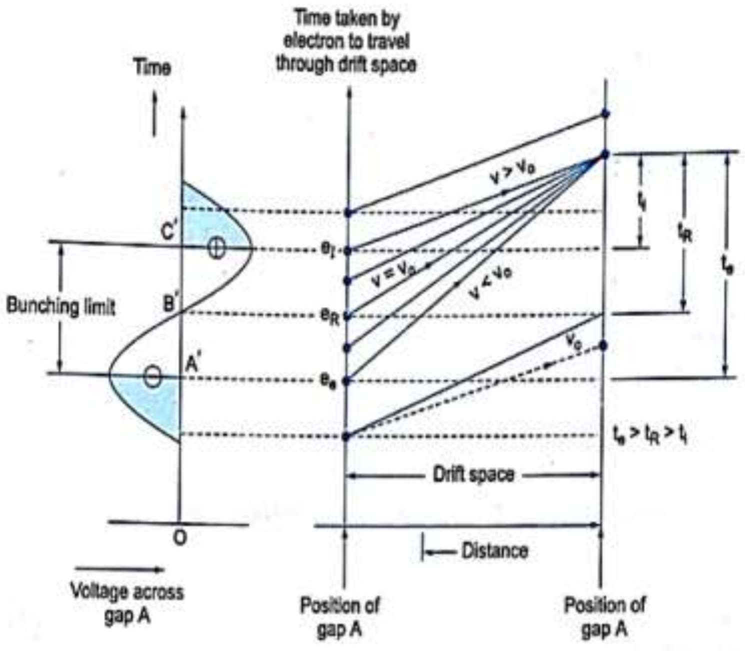
- The input and output are taken from the tube via resonant cavities with the aid of coupling loops.



Two Cavity Klystron Amplifier

Operation:

- The RF signal to be amplified is used for exciting the input buncher cavity thereby developing an alternating voltage of signal frequency across the gap A.
- Let us now consider the effect of this gap voltage on the electron beam passing through gap A.
- This situation is best explained by means of an Applegate diagram



Two Cavity Klystron Amplifier

- At point B’ on the input RF cycle, the alternating voltage is zero and going positive.
- At this instant, the electric field across gap A is zero and an electron which passes through gap A at this instant is unaffected by the RF signal.
- Let this electron be called the reference electron e_R which travels with an unchanged velocity $v_0 = \sqrt{2eV/m}$. Where V is the anode to cathode voltage.
- At point C’ of the input RF cycle an electron which leaves gap A later than reference electron e_R, called the late electron e_l is subjected to maximum positive RF voltage and hence travels towards gap B with an increased velocity ($v > v_0$) and this electron tries to overtake the reference electron e_R.
- Similarly an early electron e_e that passes the gap A’ slightly before the reference electron e_R is subjected to a maximum negative field.

Two Cavity Klystron Amplifier

- Hence this early electron is decelerated and travels with reduced velocity v_0.
- This electron e_e falls back and reference electron e_R catches up with the early electron.
- Therefore the velocity of the electron varies in accordance with RF input voltage, resulting in velocity modulation of the electron beam.
- As a result of these actions, the electrons in the bunching limit (between point A' and C') gradually bunch together as they travel down the drift space, from gap A to gap B.
- The density of electrons passing the gap B vary cyclically with time, that is the electron beam contains an ac current and is current modulated.
- The drift space converts the velocity modulation into current modulation.

Two Cavity Klystron Amplifier

- Bunching occurs only once per cycle centered around the reference electron.

- With proper design (optimum gap widths, anode to cathode voltage, drift space length etc.), a little RF power applied to the buncher cavity results in large beam currents at the catcher cavity with a considerable power gain.

- **Performance Characteristics:**
  - Frequency : 250 MHz to 100 GHz (60 GHz nominal).
  - Power : 10kW - 500 kW (CW) 30 MW (Pulsed).
  - Power gain : 15 dB - 70 dB (60 dB nominal).
  - Bandwidth : 10 - 60 MHz
  - Noise figure : 12 - 20 dB
  - Theoretical efficiency : 58% (30% - 40% nominal).

Two Cavity Klystron Amplifier

- **Applications**
  1. As power output tubes
     - In UHF TV transmitters.
     - In troposphere scatter transmitters.
     - Satellite Communication ground stations.
     - Radar transmitters.
  2. As power oscillator (5 - 50 GHz) if used as a klystron amplifier.

Two Cavity Klystron Amplifier(Mathematical analysis)

Mathematical analysis of a klystron amplifier

Let the dc voltage between cathode and anode be V_0 and v_0 be the velocity of the electron, L be the drift space length and the RF input signal to be amplified by the klystron be V_s.

Then

$$v_0 = \sqrt{\frac{2\,eV_0}{m}} = 0.593 \times 10^6 \sqrt{v_0}\ \text{m/sec} \longrightarrow \textcircled{1}$$

$$V_s = V_1 \sin \omega t \longrightarrow \textcircled{2}$$

where V_1 = amplitude of the signal and $V_1 << V_0$

The energy of the electron at the time of leaving buncher cavity is given by

$$\frac{1}{2} m v_1^2 = e\,(V_0 + V_1 \sin \omega t_1)$$

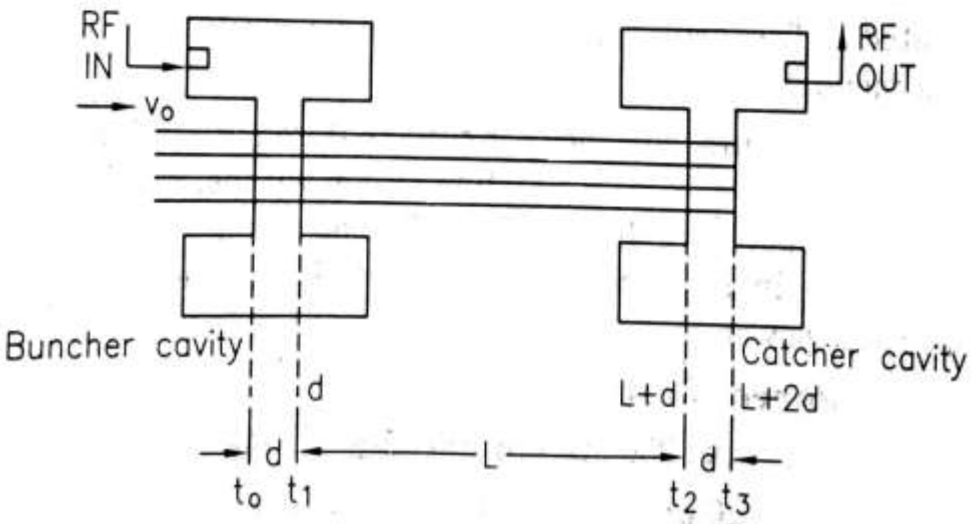
Two Cavity Klystron Amplifier(Mathematical analysis)

$$v_1 = \sqrt{\frac{2\,e\,(V_0 + V_1 \sin \omega t_1)}{m}}$$

$$= \sqrt{\frac{2\,eV_0}{m}} \cdot \sqrt{1 + \frac{V_1}{V_0} \sin \omega t_1}$$

$V_1 << V_0$,

$$v_1 = v_0 \left(1 + \frac{V_1}{V_0} \sin \omega t_1\right)^{1/2}$$



Two Cavity Klystron Amplifier(Mathematical analysis)

- Expanding binomially and neglecting higher powers of $\sin\omega t$ we get

$$v_1 = v_0\left(1 + \frac{V_1}{2\,V_0}\sin\,\omega t_1\right) \longrightarrow ③$$

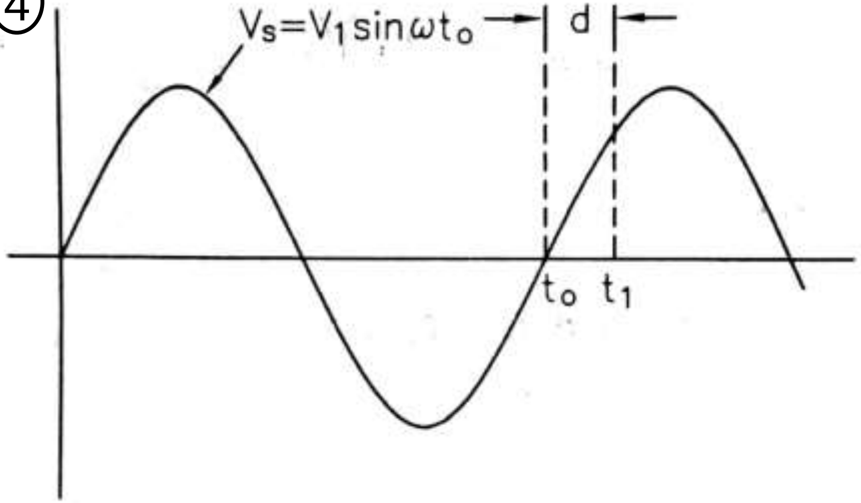
This is the equation of velocity modulation.

Two Cavity Klystron Amplifier(Mathematical analysis)

$$\omega t_1 = \omega t_0 + \frac{\theta_g}{2}$$

Where θ_g is the phase angle of the RF input voltage during which the electron is accelerated (refer below fig)

$$\theta_g = \omega t = \omega (t_1 - t_0) = \frac{\omega d}{v_0} \longrightarrow ④$$



$$v_{1\,(\max)} = v_0 \left(1 + \frac{V_1}{2V_0}\right) \longrightarrow ⑤$$

$$v_{1\,(\min)} = v_0 \left(1 - \frac{V_1}{2\,V_0}\right) \longrightarrow ⑥$$

Two Cavity Klystron Amplifier(Mathematical analysis)

- If the distance in the drift space at which the bunching occurs from the buncher grid at time t_1 is L_1 (from below fig)

$$L_1 = v_0\,(t_1 - t_0) \longrightarrow \textcircled{7}$$

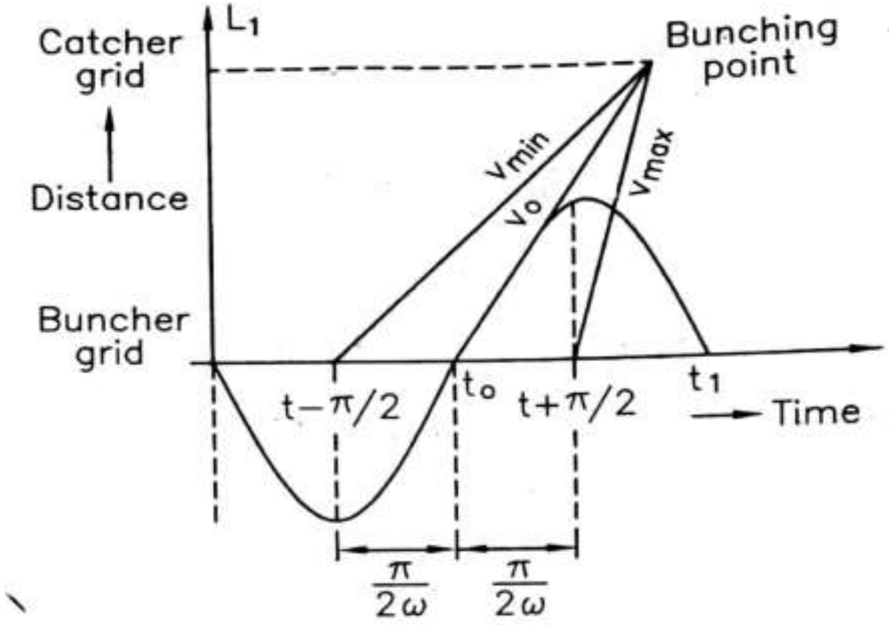
$$L_1 \text{ at } t_{-\pi/2} = v_{\min}\,(t_1 - t_{-\pi/2}) \longrightarrow \textcircled{8}$$

$$L_1 \text{ at } t_{+\pi/2} = v_{\max}\,(t_1 - t_{+\pi/2}) \longrightarrow \textcircled{9}$$

$$\left.\begin{aligned} t_{-\pi/2} &= t_0 - \pi/2\omega \\ t_{+\pi/2} &= t_0 + \pi/2\omega \end{aligned}\right| \longrightarrow \textcircled{10}$$

$$L_1 \text{ at } t_{-\pi/2} = v_0\left(1 - \frac{V_1}{2V_0}\right)\left(t_1 - t_0 + \frac{\pi}{2\omega}\right)$$

$$L_1 \text{ at } t_{+\pi/2} = v_0\left(1 + \frac{V_1}{2V_0}\right)\left(t_1 - t_0 - \frac{\pi}{2\omega}\right)$$



Two Cavity Klystron Amplifier(Mathematical analysis)

$$L_1 = v_0\,(t_1 - t_0) + v_0\left[\frac{\pi}{2\omega} - \frac{V_1}{2V_0}(t_1 - t_0) - \frac{V_1}{2V_0}\,\frac{\pi}{2\omega}\right]$$

If the distance has to be the same for $-\frac{\pi}{2}$, 0, $+\frac{\pi}{2}$ bunches, L_1 for all three should be equal to $v_0\,(t_1 - t_0)$

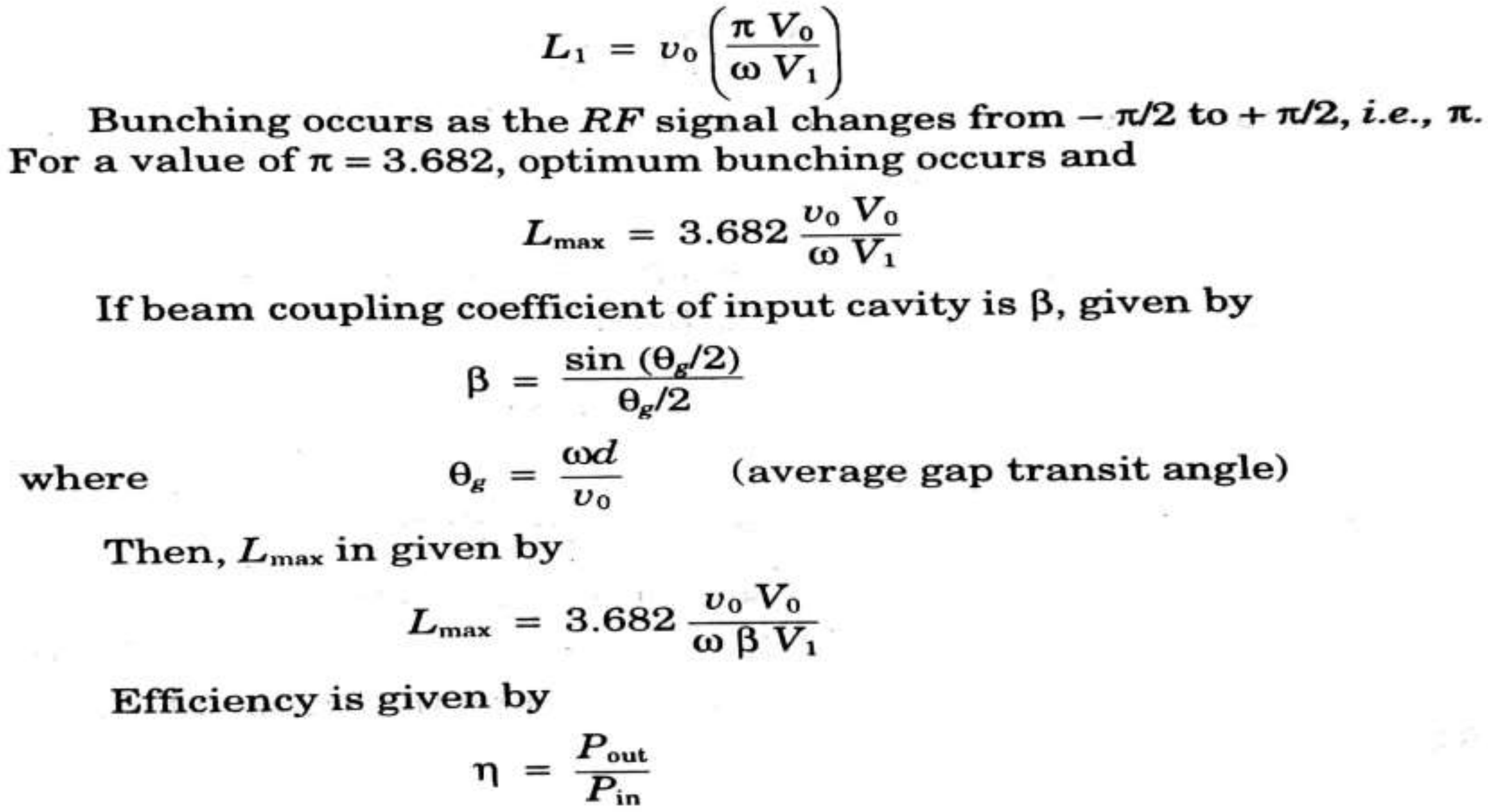
$$\frac{\pi}{2\omega} - \frac{V_1}{2V_0}(t_1 - t_0) - \frac{V_1}{2V_0}\,\frac{\pi}{2\omega} = 0$$

$$-(t_1 - t_0) = \frac{\pi}{2\omega}\left[\frac{V_1}{2V_0} - 1\right]\cdot\frac{2V_0}{V_1}$$

$$= \frac{\pi}{2\omega} - \frac{\pi\,V_0}{\omega\,V_1}$$

$\frac{V_0}{V_1}$ $\qquad$ $\frac{\pi}{2\omega}$ $\qquad$ $t_1 - t_0 \approx \frac{\pi\,V_0}{\omega\,V_1}$

Two Cavity Klystron Amplifier(Mathematical analysis)



$$L_1 = v_0 \left(\frac{\pi V_0}{\omega V_1} \right)$$

Bunching occurs as the *RF* signal changes from $-\pi/2$ to $+\pi/2$, *i.e.*, π. For a value of $\pi = 3.682$, optimum bunching occurs and

$$L_{\max} = 3.682 \frac{v_0 V_0}{\omega V_1}$$

If beam coupling coefficient of input cavity is β, given by

$$\beta = \frac{\sin(\theta_g/2)}{\theta_g/2}$$

where $$\theta_g = \frac{\omega d}{v_0}$$ (average gap transit angle)

Then, $L_{\max}$ in given by

$$L_{\max} = 3.682 \frac{v_0 V_0}{\omega \beta V_1}$$

Efficiency is given by

$$\eta = \frac{P_{out}}{P_{in}}$$

Two Cavity Klystron Amplifier(Mathematical analysis)

$$\text{RF voltage} = V_2 \sin \omega t_2.$$

Energy given by the electron to the bunch $= (-e) V_2 \sin \omega t_2 = -e V_2 \sin \omega t_2.$

The average energy given to the RF field in a cycle

$$P_{av} = \frac{1}{2\pi} \int_{\omega t_1 = 0}^{\omega t_2 = 2\pi} (-e V_2 \sin \omega t_2) \, d\omega t_1$$

$$T = t_2 - t_1 = \frac{L}{v_1} = \frac{L}{\left(v_0 \left(1 + \frac{V_1}{V_0}\right) \sin \omega t_1\right)^{1/2}}$$

$$= \frac{L}{v_0}\left[1 - \frac{V_1}{2 V_0} \sin \omega t_1\right]$$

Two Cavity Klystron Amplifier(Mathematical analysis)

Multiplying by ω

$$\omega T = \omega (t_2 - t_1) = \frac{\omega L}{v_0}\left[1 - \frac{V_1}{2V_0}\sin \omega t_1\right]$$

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

The transit time without RF voltage V_1 in buncher cavity

$$\frac{\omega L}{v_0} = \omega T_0 = \theta_0 = 2\pi N$$

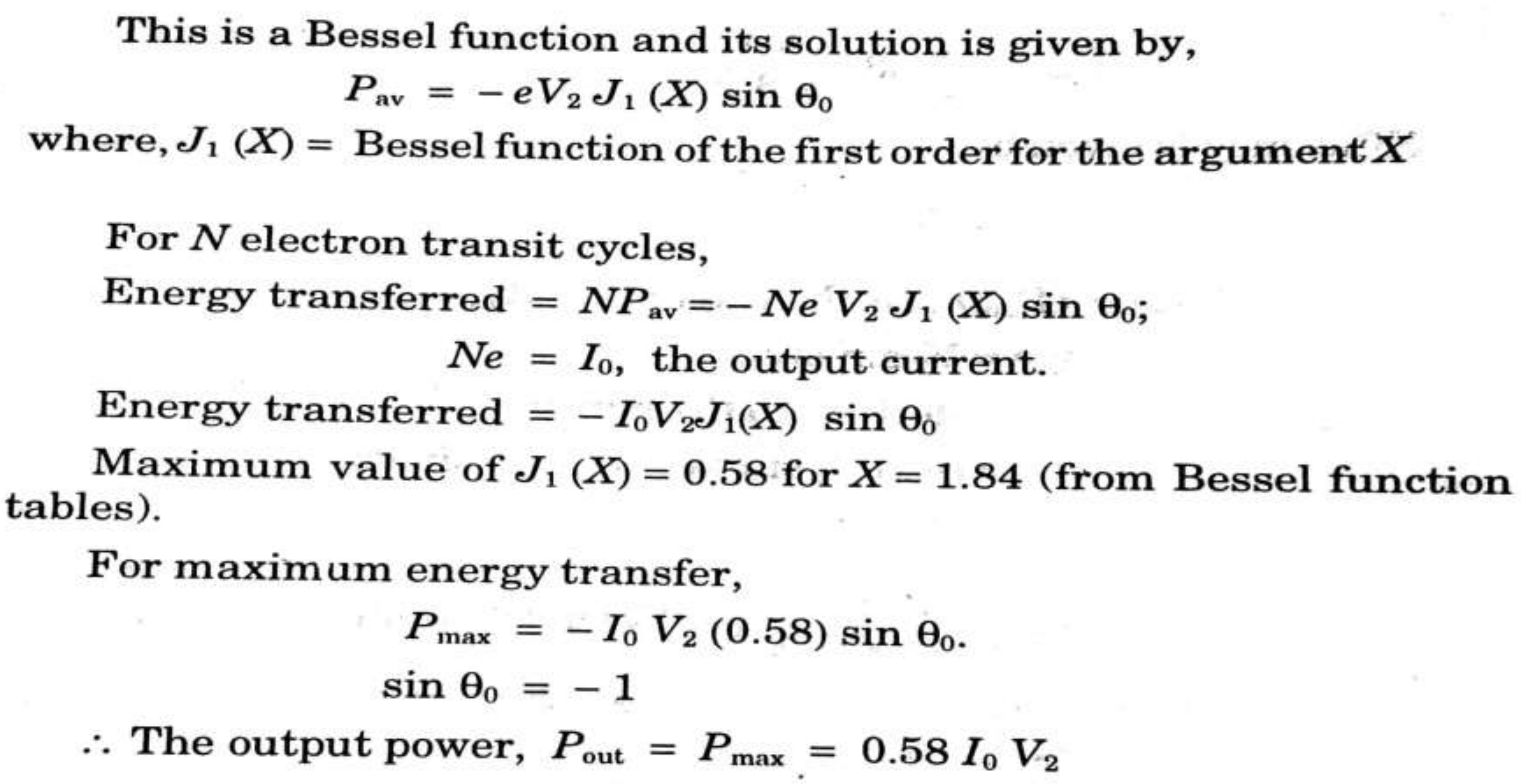
Where N is the number of electron transit cycles in drift space

$$X = \frac{V_1}{2V_0}\theta_0$$

Now $$P_{av} = \frac{-eV_2}{2\pi}\int_0^{2\pi} \sin(\omega t_1 + T)\, d\omega t_1.$$

$$P_{av} = \frac{-eV_2}{2\pi}\int_0^{2\pi} \sin\left[\omega t_1 + \theta_0\left(1 - \frac{V_1}{2V_0}\sin \omega t_1\right)\right] d\omega t_1$$

Two Cavity Klystron Amplifier(Mathematical analysis)



This is a Bessel function and its solution is given by,

$$P_{av} = -eV_2 J_1(X) \sin \theta_0$$

where, $J_1(X)$ = Bessel function of the first order for the argument X

For N electron transit cycles,

$$\text{Energy transferred} = NP_{av} = -Ne\, V_2\, J_1(X) \sin \theta_0;$$

$$Ne = I_0, \text{ the output current.}$$

$$\text{Energy transferred} = -I_0 V_2 J_1(X) \sin \theta_0$$

Maximum value of $J_1(X) = 0.58$ for $X = 1.84$ (from Bessel function tables).

For maximum energy transfer,

$$P_{max} = -I_0\, V_2\, (0.58) \sin \theta_0.$$

$$\sin \theta_0 = -1$$

$$\therefore \text{ The output power, } P_{out} = P_{max} = 0.58\, I_0\, V_2$$

Two Cavity Klystron Amplifier(Mathematical analysis)

- The input power is basically the dc input given by

$$P_{in} = I_0 V_0$$

The efficiency (η) is given by

$$\eta = \frac{P_{out}}{P_{in}} = \frac{0.58\, I_0 V_2}{I_0 V_0} = 0.58 \frac{V_2}{V_0}$$

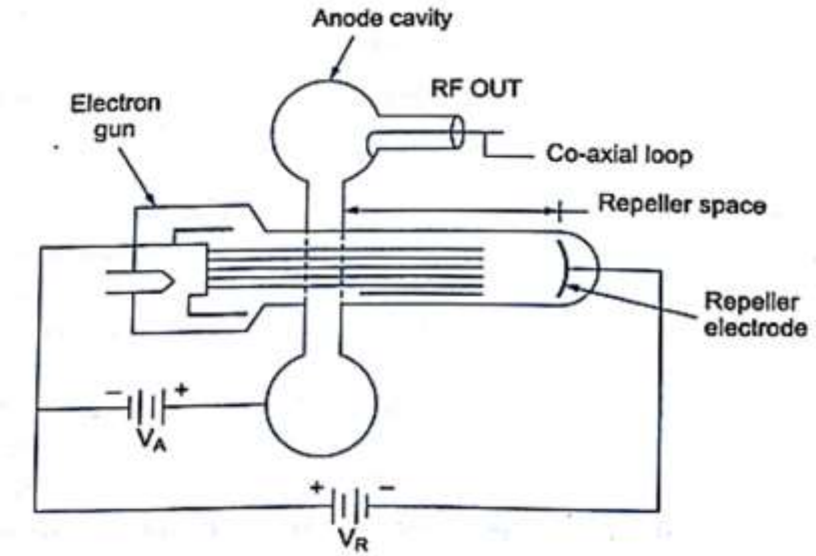
- As V_2 is always less than V_0, the maximum efficiency that can be attained is 0.58 or 58%. The typical value of gain for two cavity tubes is 10-20 dB.

Reflex Klystron

- The reflex klystron is a single cavity variable frequency microwave generator of low power and low efficiency.

- This is most widely used in applications where variable frequency is desired as
  1. In 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.

Reflex Klystron



Construction

It consists of an electron gun, a filament surrounded by cathode and a focusing electrode at cathode potential as shown in Fig.

The electron beam is accelerated towards the anode cavity (positive potential).

After passing the gap in the cavity; electrons travel towards a repeller electrode which is at a high negative potential VR.

Reflex Klystron

- The electrons never reach the repeller because of the negative field and are returned back towards the gap.
- Under suitable conditions, the electrons give more energy to the gap than they took from the gap on their forward journey and oscillators are sustained.

Reflex Klystron

The RF voltage that is produced across the gap by the cavity oscillations act on the electron beam to cause velocity modulation.

eR is the reference electron that passes through the gap when the gap voltage is 0 and going negative.

Electron eR is unaffected by the gap voltage.

This moves towards the repeller and gets reflected by the negative voltage on the repeller.

It returns and passes through the gap for a second time.

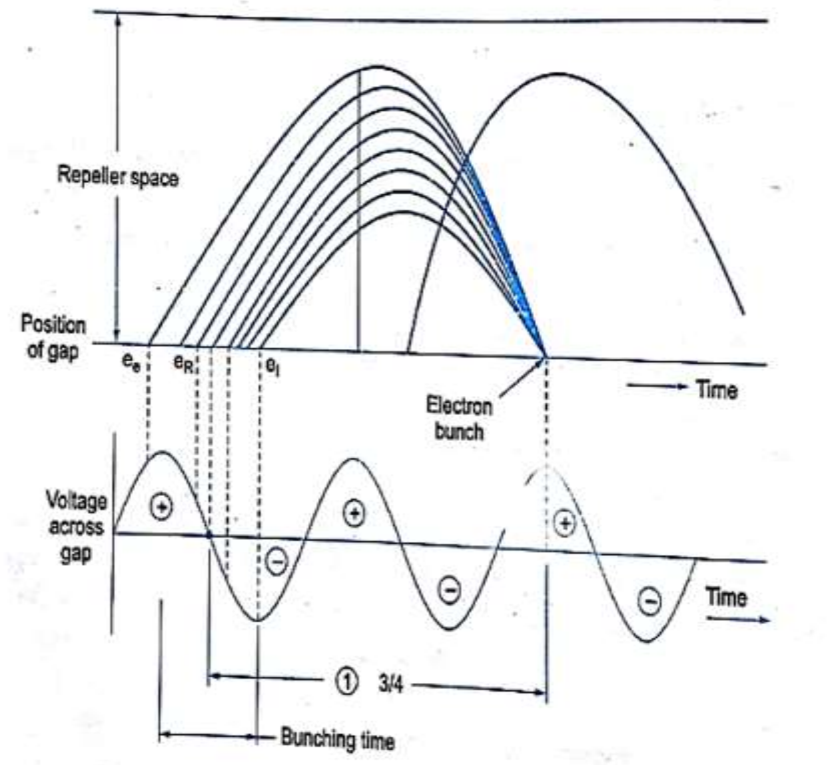


Fig. Applegate diagram

Reflex Klystron

- The early electron ee that passes through the gap before the reference electron eR experiences a max positive voltage across the gap and this electron is accelerated.
- It moves with greater velocity and penetrates deep into repeller space.
- The return time for electron ee is greater as the depth of penetration into the repeller space is more.
- Hence ee and eR appears at the gap for the second time at the same instant.
- The late electron el that passes the gap later than reference electron eR experiences a maximum negative voltage and moves with a retarding velocity.
- The return time is shorter as the penetration into repeller space is less and catches up with eR and ee electrons forming a bunch.
- Bunches occur once per cycle centered around the reference electron eR and these bunches transfer maximum energy to the gap to get sustained oscillations

Reflex Klystron

- For oscillations to be sustained, the time taken by the electrons to travel into the repeller space and back to the gap is called transit time.
- Returning of electrons after $1\frac{3}{4}$ or $2\frac{3}{4}$ or $3\frac{3}{4}$ cycles etc.
- In general, the optimum transit time should be

$$T=n+\frac{3}{4}$$

Where n is any integer.

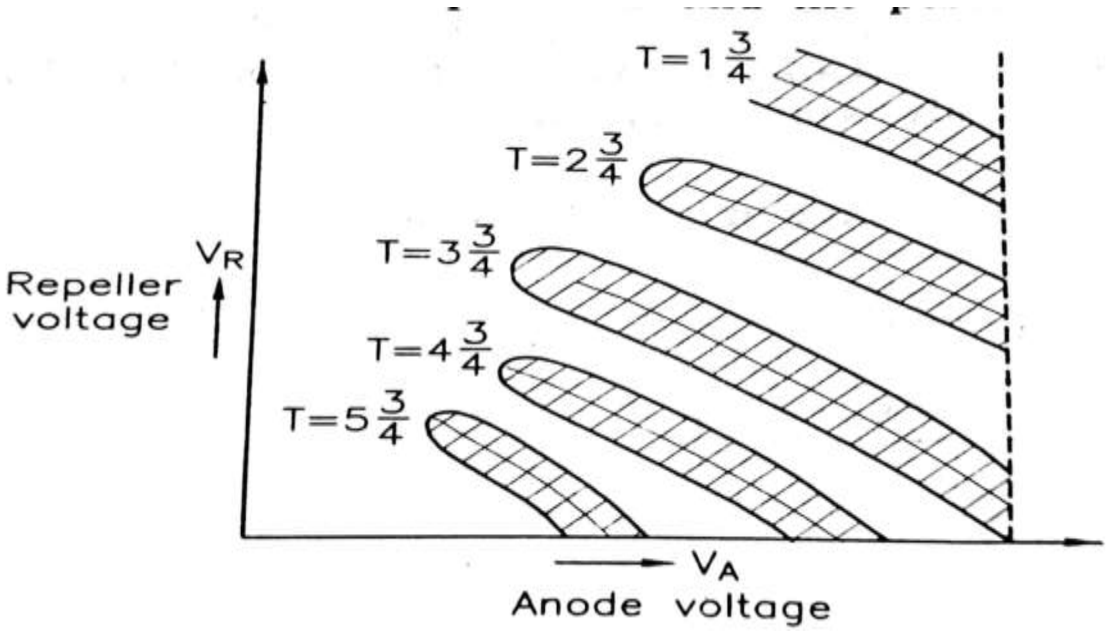
Reflex Klystron

Operating Characteristics

1. **Voltage Characteristics:**

- Oscillations can be obtained only for specific combinations of anode and repeller voltages that give a favorable transit time ($T=n+\frac{3}{4}$)
- The earlier the mode the larger the output power.
- But the voltages required are also higher as shown in fig leading to insulation problems and the possibilities of lower efficiencies.
- As a results the modes corresponding to n=2 or n=3 are mostly widely used.

Reflex Klystron



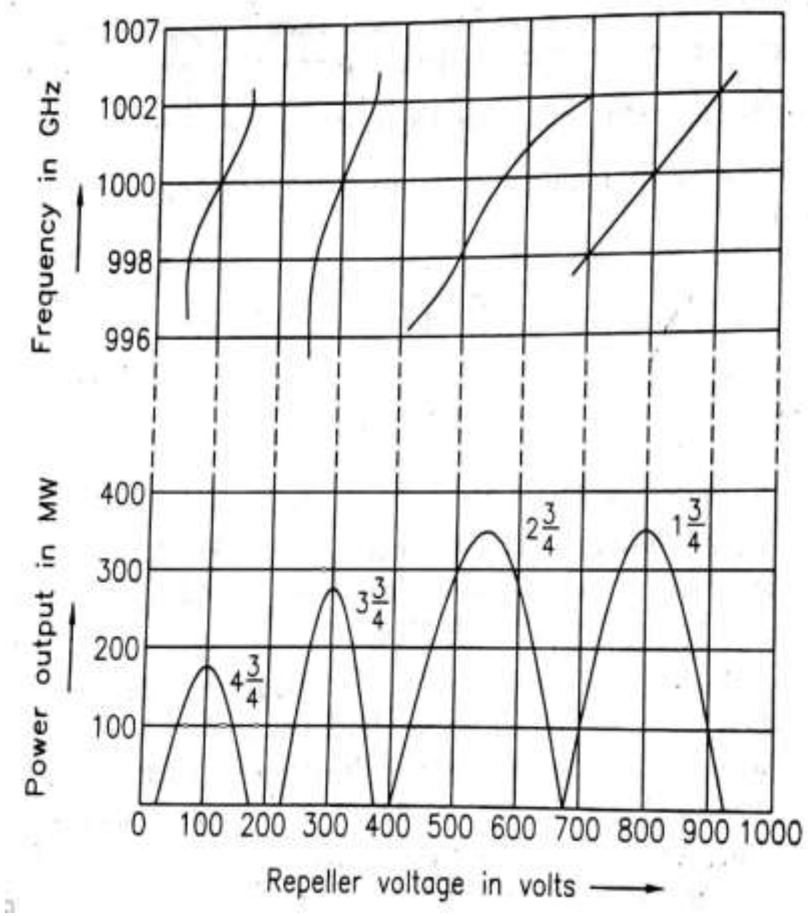
Reflex Klystron

2. Power output and frequency characteristics:

The frequency of resonance of the cavity decides the frequency of oscillation.

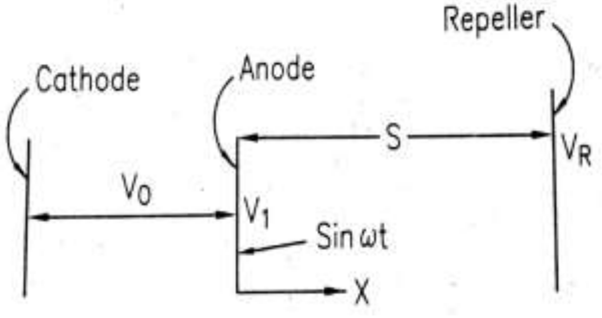
Variations of repeller voltage slightly changes the frequency.

This makes it possible to use reflex klystron as a voltage tuned oscillator or frequency modulated oscillator.



Reflex Klystron(Mathematical Analysis)

Consider this figure for the mathematical analysis of reflex klystron



V_o= electron gun anode voltage

$V_1\ sin\omega t$= RF voltage at cavity gap

V_R= Repeller voltage with respect to cathode

S = distance between cavity gap and repeller electrode

v_o= velocity of electron in gun

v_1= velocity due to RF voltage in addition to the electron accelerating voltage V_o.

t_o= time for electron entering cavity gap at x=0

t_1= time for same electron leaving cavity gap at x=d

t_2= time for same electron returned by retarding field at x=d

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$$v_0 = \sqrt{\frac{2eV_0}{m}} \qquad \left(\text{since } \frac{1}{2} m v_0^2 = e V_0\right)$$

$$v_1 = V_0 \sqrt{\frac{1 + V_1}{V_0}} \sin \omega t$$

Voltage between repeller and anode $= V_R - (V_0 + V_1 \sin \omega t) \approx V_R - V_0.$

Retarding electrostatic field between repeller and anode is given by $E = -\left(\frac{V_R - V_0}{s}\right)$

Force on electron = $-eE = +e\left(\frac{V_R - V_0}{s}\right)$

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- Also, force on electron = mass * acceleration = $\frac{md^2x}{dt^2}$

$$m\frac{d^2x}{dt^2} = \frac{+e}{s}(V_R - V_0)$$

$$\frac{d^2x}{dt^2} = \frac{e}{ms}(V_R - V_0)$$

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integrating once

$$\frac{dx}{dt} = \frac{e}{ms}(V_R - V_0)\, t + C$$

$$t = t_1, \quad \frac{dx}{dt} = v_1$$

$$v_1 = \frac{e}{ms}(V_R - V_0)\, t_1 + C$$

$$C = v_1 - \frac{e}{ms}(V_R - V_0)\, t_1$$

Substituting ‘C’ in eq 3

$$\frac{dx}{dt} = \frac{e}{ms}(V_R - V_0)\,(t - t_1) + v_1$$

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integrating again

$$x = \frac{e}{2\,ms}(V_R - V_0)\,(t - t_1)^2 + v_1\,t + C_1$$

At x=0 i.e., at the point of return from repeller space $t = t_2$

$$0 = \frac{e}{2\,ms}(V_R - V_0)\,(t_2 - t_1)^2 + v_1\,t_2 + C_1$$

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$$C_1 = -\frac{e}{2\,ms}(V_R - V_0)\,(t_2 - t_1)^2 - v_1\,t_2$$

Using the value of C_1 in eq 4

$$x = \frac{e}{2\,ms}(V_R - V_0)\,[(t - t_1)^2 - (t_2 - t_1)^2\,] + v_1\,(t - t_2)$$

Again when $t = t_1$, $x = 0$,

$$-\frac{e}{2\,ms}(V_R - V_0)\,(t_2 - t_1)^2 - v_1\,(t_2 - t_1) = 0$$

$(t_2 - t_1)$ is the round trip transit time and is given by

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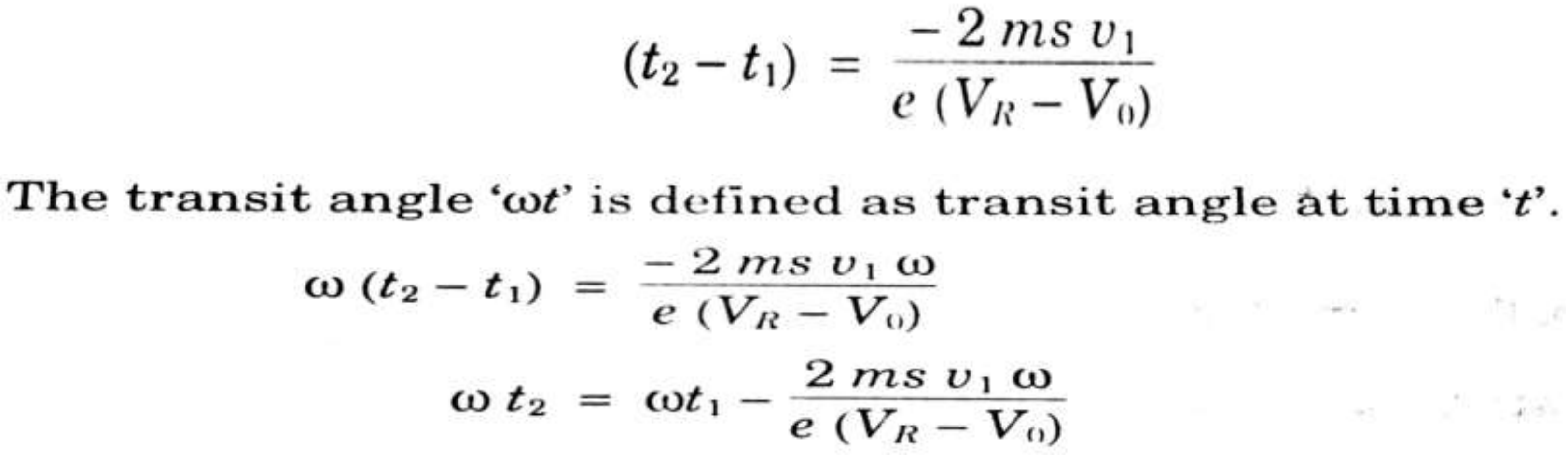

$$(t_2 - t_1) = \frac{-2\,ms\,v_1}{e\,(V_R - V_0)}$$

The transit angle 'ωt' is defined as transit angle at time 't'.

$$\omega\,(t_2 - t_1) = \frac{-2\,ms\,v_1\,\omega}{e\,(V_R - V_0)}$$

$$\omega\,t_2 = \omega t_1 - \frac{2\,ms\,v_1\,\omega}{e\,(V_R - V_0)}$$

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$$v_1 = v_0 \left(1 + \frac{V_1}{V_0} \sin \omega t\right)^{1/2}$$

$V_1 << V_0,$

$$v_1 \approx v_0 \left(1 + \frac{V_1}{2\,V_0} \sin \omega t\right)$$

Substituting for v_1

$$\omega t_2 = \omega t_1 - \frac{2\,ms\omega}{e\,(V_R - V_0)} \cdot v_0 \left(1 + \frac{V_1}{2\,V_0} \sin \omega t\right)$$

Let $$-\frac{2\,ms\omega\, v_0}{e\,(V_R - V_0)} = \omega\, T_0'\, X = \theta_0' \qquad \longrightarrow$$ ⑥

θ_0'

Let $\frac{V_1}{2\,V_0}\,\theta_0' = X'$ where X' is the bunching parameter

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Substituting in eq 5

$$\omega t_2 = \omega t_1 + \theta_0' \left(1 + \frac{V_1}{2V_0} \sin \omega t\right)$$

Relation between Repeller Voltage and Accelerating voltage

W K T center of bunch electrons is unaffected by the RF voltage when

$$V_1 << V_0$$

$$\omega t_2 = \omega t_1 + \theta_0'$$

For maximum transfer of energy, the modes are $1\frac{3}{4}$ cycles apart

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$2\pi(n - 1/4)$ where $n - 1/4 = 3/4, 1\frac{3}{4}$ etc.

The optimum value of θ_0' is

$$\theta_0' = (2\pi n - \pi/2)$$

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- From eq 6

$$\theta_0' = -\frac{2\,ms\omega}{e\,(V_R - V_0)} \cdot v_0$$

$$v_0 = -\frac{e\,(V_R - V_0)}{2\,ms\omega} \cdot \theta_0'.$$

$$v_0^2 = \frac{e^2\,(V_R - V_0)^2\,(\theta_0')^2}{4\,\omega^2 m^2 s^2}$$

$$\frac{1}{2}\,mv_0^2 = eV_0$$

$$V_0 = \frac{m}{2e} \cdot v_0^2$$

$$V_0 = \frac{m}{2e} \cdot \frac{e^2\,(V_R - V_0)^2\,(\theta_0')^2}{4\omega^2 m^2 s^2}$$

where $\theta_0' = 2\,\pi n - \frac{\pi}{2}$

$$\therefore \qquad \frac{V_0}{(V_R - V_0)^2} = \frac{m}{2e}\,\frac{e^2}{4\,\omega^2\,m^2\,s^2}\left(2\,\pi n - \frac{\pi}{2}\right)^2$$

Simplifying,

$$\frac{V_0}{(V_R - V_0)^2} = \frac{1}{8} \cdot \frac{1}{\omega^2 s^2}\,\frac{e}{m}\left(2\,\pi n - \frac{\pi}{2}\right)^2$$

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Expression for change in frequency due to repeller voltage variation electronic tuning of reflex klystron

$$(V_R - V_0)^2 = \frac{8\,ms^2\,V_0}{\left(2\,\pi n - \frac{\pi}{2}\right)^2 \cdot e} \cdot \omega^2$$

Differentiating V_R with respect to ω.

$$2\,(V_R - V_0)\,\frac{dV_R}{d\omega} = \frac{16\,ms^2\,V_0}{(2\,\pi n - \pi/2)^2 \cdot e} \cdot \omega$$

or

$$\frac{d\,V_R}{d\omega} = \frac{8\,ms^2\,V_0\,\omega}{e\left(2\,\pi n - \frac{\pi}{2}\right)^2} \cdot \frac{1}{(V_R - V_0)}$$

We can resubstitute the value of $(V_R - V_0)$ as,

$$(V_R - V_0) = \sqrt{\frac{8\,ms^2\,V_0\,\omega^2}{e\,(2\,\pi n - \pi/2)^2}}$$

$$\frac{d\,V_R}{d\omega} = \frac{8\,ms^2\,V_0\,\omega}{e\,(2\,\pi n - \pi/2)^2} \times \sqrt{\frac{e\,(2\,\pi n - \pi/2)^2}{8\,ms^2\,V_0\,\omega^2}}$$

$$= \sqrt{\frac{8\,ms^2\,V_0}{e}} \cdot \frac{1}{(2\,\pi n - \pi/2)}$$

$$\frac{d\,V_R}{df} = \frac{2\,\pi s}{(2\,\pi n - \pi/2)} \sqrt{\frac{8\,mV_0}{e}}$$

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Efficiency of Reflex klystron

It is the ratio between the maximum power transferred to the output of klystron to the power input to the klystron.

$$\eta = \frac{P_{output}}{P_{input}}$$

DC power supplied by the beam voltage VO is

$$P_{dc} = V_0 I_0$$

AC power delivered

$$P_{ac} = I_0 V_2 J_1 (X') \sin \theta_0'$$

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- As the current flows in the negative direction, the negative sign becomes positive and $\sin \theta_0'$ is 1 and V_2 is V_1 being single and same cavity.

$$P_{ac} = I_0 V_1 J_1(X')$$

$$X' = \frac{V_1}{2\,V_0} \cdot \theta_0' \left(= 2\,n\pi - \frac{\pi}{2} \right)$$

$$\frac{V_1}{V_0} = \frac{2\,X'}{(2n\pi - \pi/2)}$$

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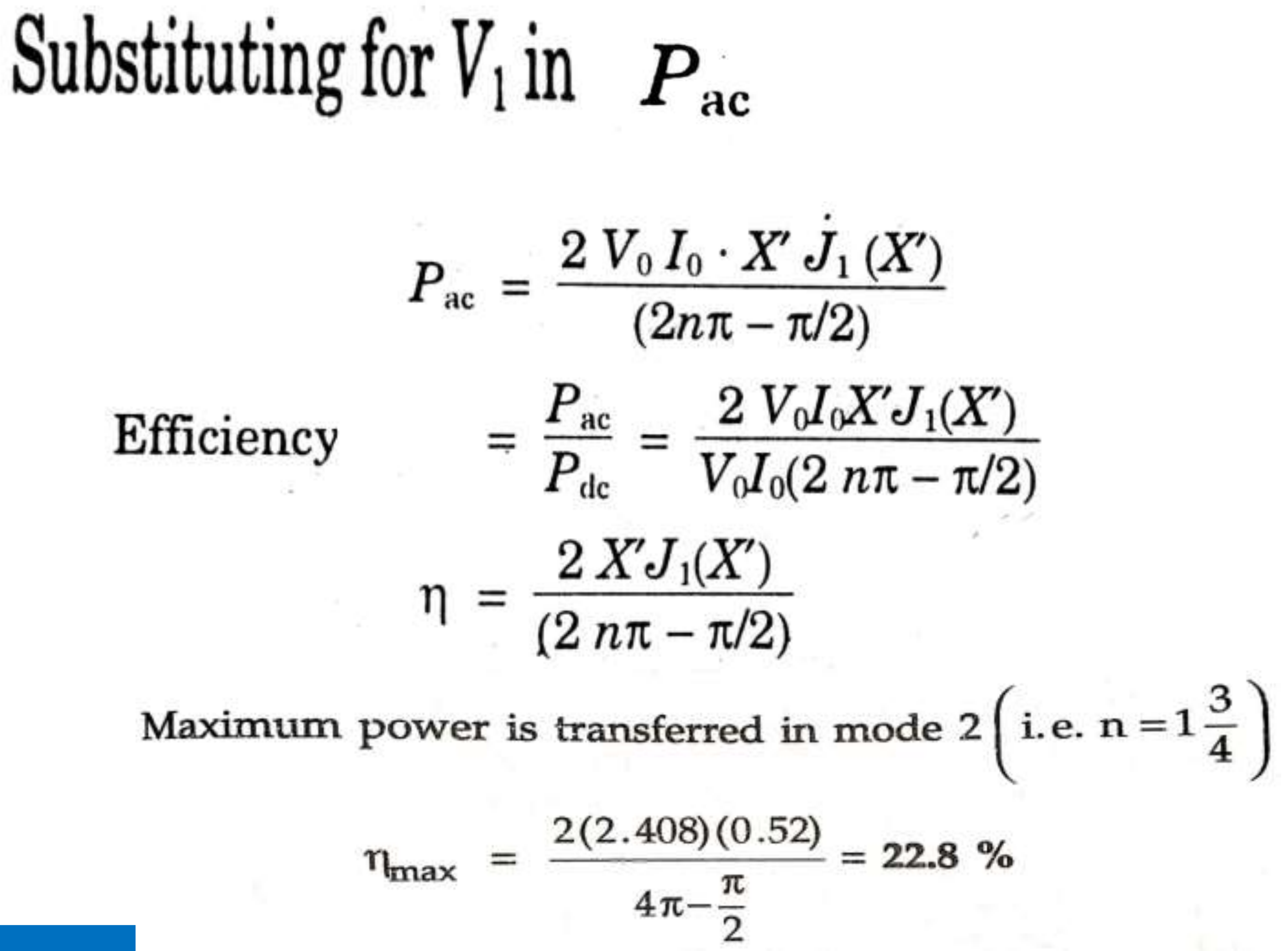


Substituting for V_1 in P_{ac}

$$P_{ac} = \frac{2\, V_0\, I_0 \cdot X'\, J_1\,(X')}{(2n\pi - \pi/2)}$$

$$\text{Efficiency} = \frac{P_{ac}}{P_{dc}} = \frac{2\, V_0 I_0 X' J_1(X')}{V_0 I_0 (2\, n\pi - \pi/2)}$$

$$\eta = \frac{2\, X' J_1(X')}{(2\, n\pi - \pi/2)}$$

Maximum power is transferred in mode 2 $\left(\text{i.e. } n = 1\frac{3}{4}\right)$

$$\eta_{max} = \frac{2(2.408)(0.52)}{4\pi - \frac{\pi}{2}} = 22.8\ \%$$

Reflex Klystron(Mathematical Analysis)

- **Power output in terms of repeller voltage**

$$P_{out} = \frac{2 V_0 I_0 X' J_1(X')}{2n\pi - \pi/2}$$

$$2n\pi - \frac{\pi}{2} = \theta_0' = \omega T_0' = \frac{2 ms\omega}{e(V_R - V_0)} v_0$$

$$P_{out} = \frac{2 V_0 I_0 X' J_1(X')}{2 ms \,.\, \omega v_0} \times (V_R - V_0) e$$

Eliminating v_0

$$P_{out} = \frac{2 V_0 I_0 X' J_1(X')}{\omega s} \times (V_R - V_0) \sqrt{\frac{e}{2 m V_0}}$$

For maximum value of $X' J_1(X') = 1.75$, we get

$$P_{max} = \frac{1.25 V_0 I_0 (V_R - V_0)}{\omega s} \times \sqrt{\frac{e}{2 m V_0}}$$

Reflex Klystron(Mathematical Analysis)

Performance characteristics of reflex klystron

1. Frequency Range : 4 to 200 GHz
2. Output Power : 1.0 mW to 2.5 W
3. Theoretical η : 22.78%
4. Practical η : 10% to 20%
5. Tuning Range : 5 GHz at 2 watts and 30 GHz at 10 mW.

HELIX TRAVELLING WAVE TUBES

- The traveling wave tube is a form of thermionic valve or tube that is used for high power microwave amplifier designs.
- The travelling wave tube can be used for wideband RF amplifier designs where even now it performs well against devices using newer technologies.
- TWTs are used in applications including broadcasting, radar and in satellite transponders.
- The TWT is still widely used despite the fact that semiconductor

technology is advancing all the time.

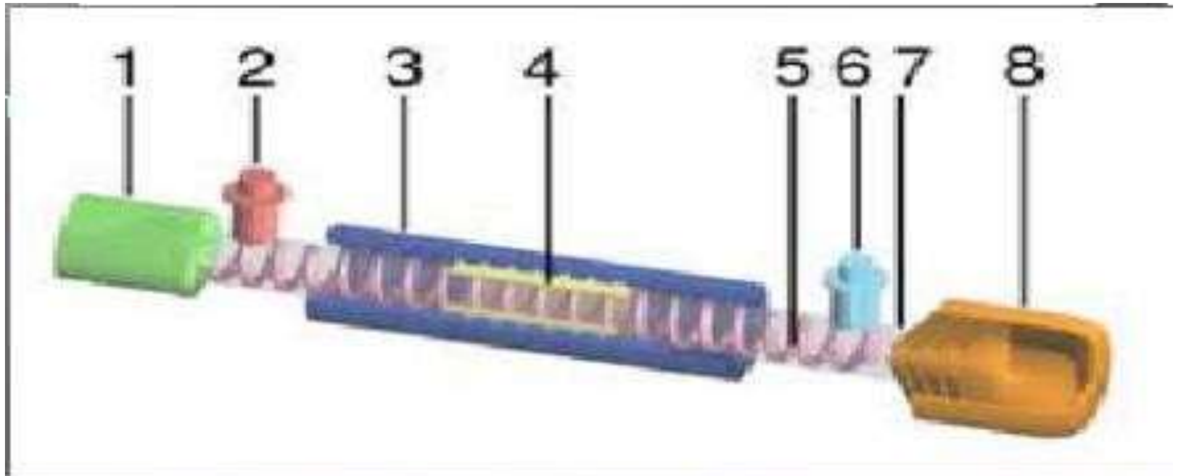
- Twotypes of TWT's are available
- LowpowerTWT
- High power TWT

HELIX TRAVELLING WAVE TUBES

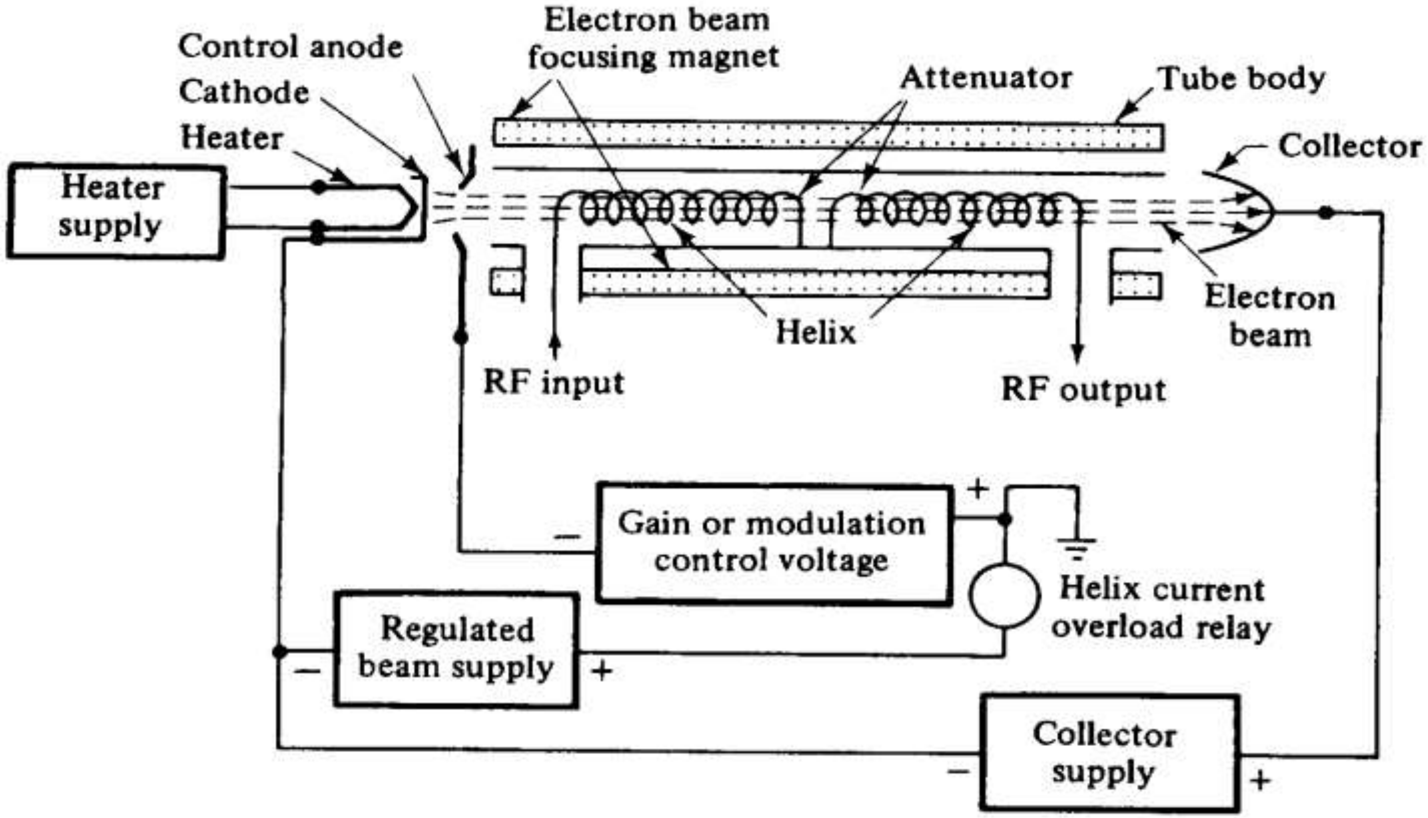
- Differences Between TWT and Klystrons:- The microwave circuit is non-resonant in TWT , while resonant circuits are used in klystrons.
- The interaction of electron beam and RF field in the TWT is continuous over the entire length of the circuit , but the interaction in the klystron occurs only at the gaps of a few resonant cavities.
- The wave in the TWT is a propagating wave , The wave in the klystron is not.
- In the couple cavity TWT there is coupling effect between the cavities, whereas each cavity in the klystron operates independently

HELIX TRAVELLING WAVE TUBE CONSTRUCTION

- The Helix Travelling wave tube(TWT) , can be split into a
- number of separate major elements:
- Vacuum tube
- Electron gun
- Magnet and
- focusing structure
- RF input
- Helix
- RF output
- Collector



Cutaway view of a TWT. (1) Electron gun; (2) RF input; (3) Magnets; (4) Attenuator; (5) Helix coil; (6) RF output; (7) Vacuum tube; (8) Collector.


Control anode
Cathode
Heater
Electron beam focusing magnet
Attenuator
Tube body
Collector
Heater supply
Helix
Electron beam
RF input
RF output
Gain or modulation control voltage
Helix current overload relay
Regulated beam supply
Collector supply
−
+
−
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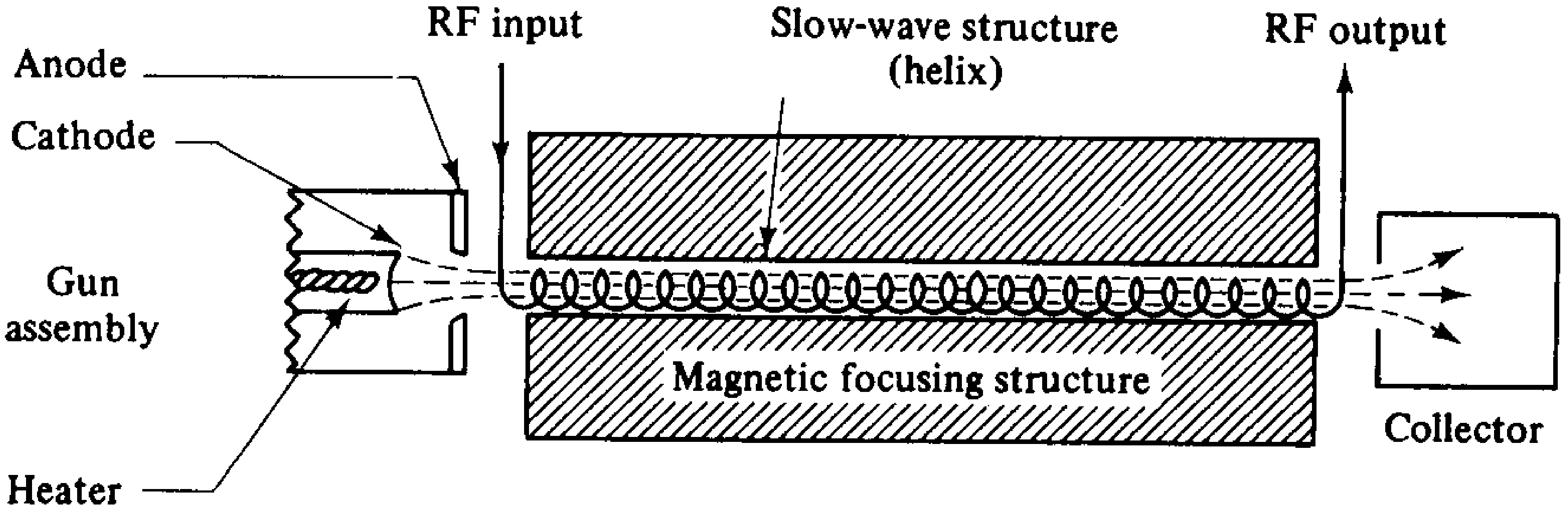
RF input
Slow-wave structure
(helix)
RF output
Anode
Cathode
Gun
assembly
Magnetic focusing structure
Collector
Heater

Working Operation:

- A Helix twt consists of an electron Gun and a Slow wave structure.
- First element-Electron gun comprising primarily of a heated cathode and grids. This produces and then accelerates a beam of electrons that travels along the length of the tube.
- The electron beam is focused by a constant magnetic field along the electron beam and the slow wave structure. This is termed as O-type traveling tube.

- The slow wave structure is either the helical type or folded-Back line. A helix is an essential part of the traveling wave tube. It acts as a delay line, in which the RF signal travels at near the same speed along the tube as the electron beam.
- The applied signal propagates around the turns of the helix and produces an electric field at the center of the helix , directed along the helix axis.
- The axial electric field progresses with a velocity that is very close to the light multiplied by the ratio of helix pitch to helix circumference.
- When the electrons enter the helix tube , an interaction takes place between the moving axial electric field and the moving electrons.
- On the average , the electrons transfer energy to the wave on the helix.
- This interaction cause the signal wave on the helix to become larger.

- Amplification process : The electrons entering the helix at zero field are not affected by the signal wave , those electrons entering the helix at the accelerating field are accelerated and those entering the helix at the retarding field are decelerated.
- As the electrons travel further along the helix , they begin forming bunch centered about those electrons that enter the helix during the zero field and collected at the collector end . The bunching shifts the phase by π/2,
- Since the dc velocity of electrons is slightly greater than the axial wave velocity, more electrons are in the retarding field than in the accelerating field. And a great amount of energy is transferred from the beam to the electromagnetic field . The amplification of the signal wave is accomplished.
- The bunch becomes more compact and a larger amplification of the signal voltage occurs at the end of the helix.

Characteristics of TWT

- The Traveling Wave Tube (TWT) is a high-gain, low-noise , wide- bandwidth microwave amplifier.
- It is capable of gains greater than 40dB with bandwidths exceeding an octave. (A bandwidth of one octave is one in which the upper cutoff frequency is twice the lower cutoff frequency.)
- Traveling-wave tubes have been designed for frequencies a slow as 300Megahertz and as high as 50 Gigahertz.
- The TWT is primarily a voltage amplifier. The wide-bandwidth and low- noise characteristics make the TWT ideal for use as an RF amplifier in microwave equipment.
- TWT amplifiers and they are typically capable of developing powers of up to 2.5 kW. For narrowband RF amplifier applications it is possible to use coupled cavity TWTs and these can deliver power levels of up to 15 Kw.
- Efficiency of 20 to 40 % is possible .

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)

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.