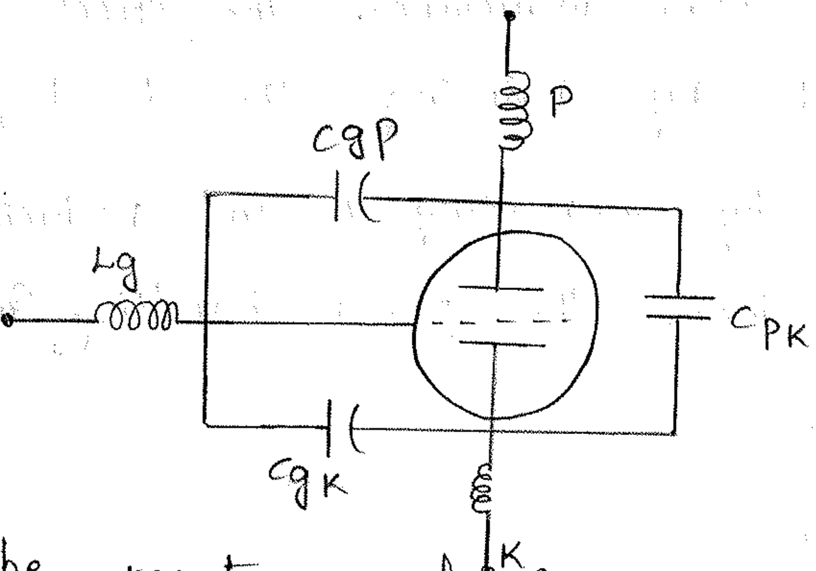
~~180~~ -3-II UNIT-IV
MWE

MICROWAVE TUBES

mitations of Conventional tubes

The Conventional devices like triode, tetrodes and pentodes are used as oscillators and amplifiers up to high frequencies (HF) for frequency >100MHz the Conventional devices are not used be case of following limitations

1) Inter Electrode Capacitance effect (IEC) :-



G - Grid
P - plate
K - Cathode

The reactance of Capacitance is $X_c = \frac{1}{2\pi f c}$

as frequency increases reactance decreases and the o/p voltage decreasinges due to shunting effect Because at higher frequency X_c becomes almost short.

The effect of IEC Can be minimized by reducing the IEC's CPK, Cgk, Cgp. These Can be reduced by decreasing the area of electrodes or by increa

-sing the distance b/w electrodes.

$$C = \frac{\mathcal{E}A}{d}$$

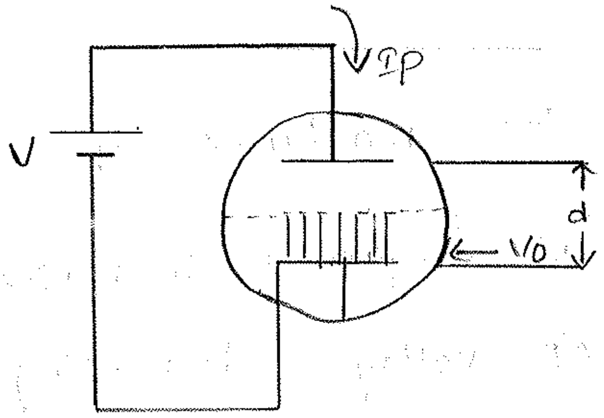
2) lead Inductance (LI) effect:-

The reactance of inductance is $X_L = 2\pi f L$ as frequency increases the voltage appear at the i/p is higher than voltage appear at the o/p this results in reduce the gain for tube amplifier.

l_K, lp and lg are lead inductances the effect of LI can be minimized by reducing the L. $L = \frac{l}{\mu_0 \mu_r A}$

L can be minimized by increasing A and reducing 'l' how ever it can reduces the power handling capacity

3) Transit time effect:-



It is defined as time taken for electron to travel from cathode to anode

ie., $\tau = \frac{d}{V_0}$.

Where d = distance b/w anode and cathode.

V_0 = velocity of electrons.

Static energy of electron is ev.

Kinetic energy of electron is $\frac{1}{2} m V_0^2$

equilibrium Condition static energy equal to

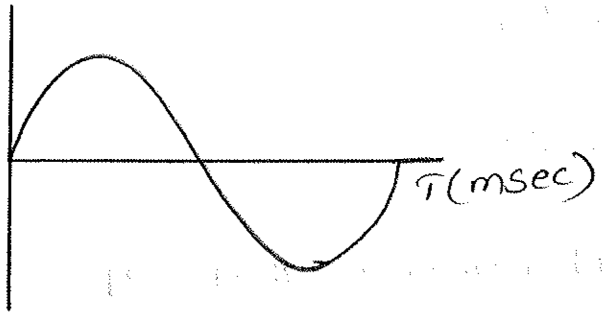
$$ev = \frac{1}{2} m v_0^2$$

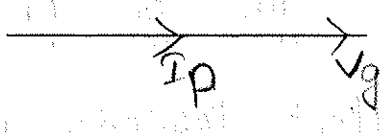
$$v_0 = \sqrt{\frac{2ev}{m}}$$

$$\boxed{\tau = \frac{1}{\sqrt{\frac{2ev}{m}}}}$$

At lower frequencies the transit time is negligible Compared to period of signal as shown in fig

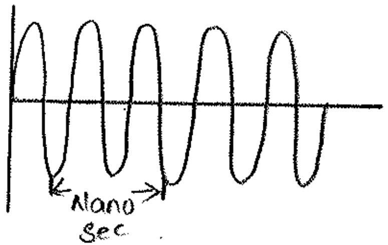
$$g_m = \frac{\Delta I_p}{\Delta V_g}$$

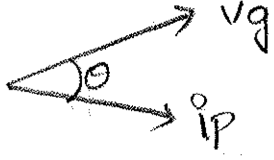




ie., both Vg and ip are in phase plate Current ip responds immediately or instantaneous to change in Control grid voltage Vg.

At higher frequency the transit time τ is Comparable with the period of signal which is very small.





* Remedy:- The transit time can be minimised by reducing the distance b/w electrodes and the plate to cathode potential is increased.

④ Gain Bandwidth limitation:-

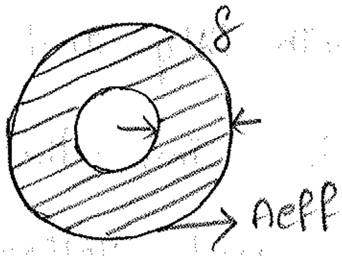
Gain Bandwidth product is always constant and independent of frequency. Hence higher gain is achieved at cost of BW only. At microwave frequencies this limitation can be minimised by use of

* Re entrant cavities.
* Slow wave structures

⑤ Effect due to RF losses:-

* Skin effect losses:- The phenomena that the field intensity with in a conductor decreases is known as skin effect

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



ie., $\delta \propto \frac{1}{\sqrt{\omega}}$ and $\delta \propto A_{eff}$.

Where A_{eff} is effective area over which current flows

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

$$R = \frac{\rho L}{A_{eff}} = \frac{\rho L}{1/\sqrt{f}}$$

$$\boxed{R = Pl\sqrt{f}}$$

As f increases R increases. There losses can be minimised by increasing size of conductor ie., ~~a~~as frequency ↑ R increases.

These losses can be reduced by increasing the size of the conductor.

ⓑ Dielectric losses :- This occur in various types of insulating materials used in the device ie., Spacers, glass envelope, Silicon and plastic encapsulation etc. the losses in any of these material is given by

$$\boxed{P = \pi f V_0^2 \varepsilon_r \tan\sigma}$$

Where ε_r = relative permitivity of dielectric.

σ = loss angle of dielectric.

As f increases the power losses increases.

→ the remedy for this is to eliminate the tube base and to reduce the surface area of glass.

⑥ Radiation losses :- When ever the dimensions of wire approach the wave length the radiation will occur ie., radiation losses increase with increased frequency

→ Remedy for this is to use proper shielding of the tubes

* Microwave tubes :- These are Constructed to Overcome the limitations of Conventional tubes. These tubes utilized the transit time effect ie, the operation of these tubes require large transit time.

The basic principle of Operation is transfer the power from a dc voltage Source to ac voltage source by means of Current density modulated electron beam.

→ Microwave tubes are two types.

* linear beam tubes. (o type)

* Cross field tubes (M type)

* linear beam tubes (o type) :- They utilize linear beam ie, the electric field axis is Coincides with that of electron beam or dc electric field.

* Ex :- Klystron, TWT, BWO.

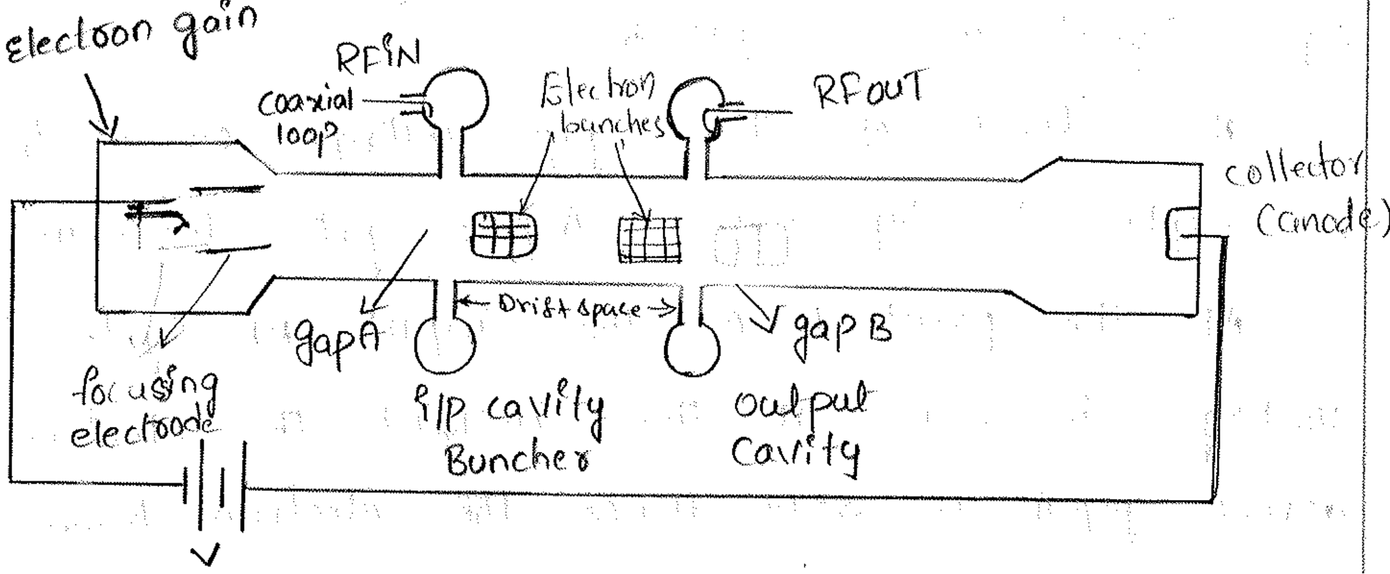
* Cross field tubes (m type) :- They utilized cross fields ie, magnetic field and electric field are perpendicular to each other.

Ex:- Magnetron.

* Klystron :- Klystron is vaccuum tube that Can be used as either generator or amplifier of "power" at microwave frequencies It was invented by Russel H Varia

at stanford university in 1939.

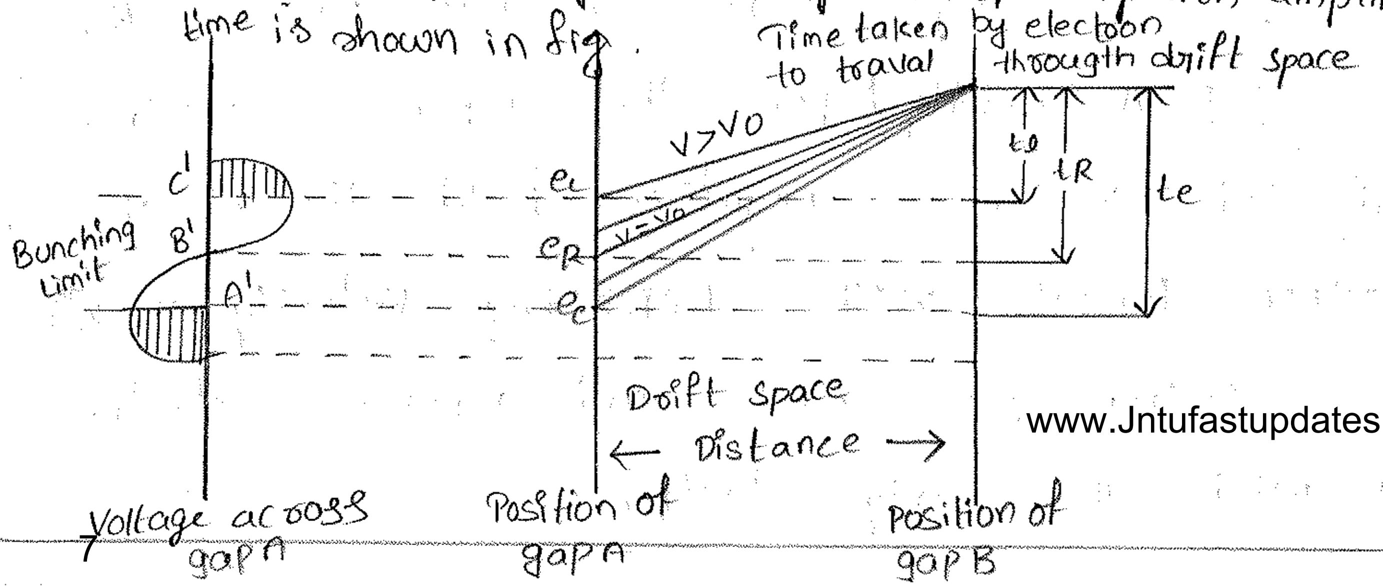
* Two Cavity klystron amplifier:-



Construction

Two Cavity klystron amplifier is basically Velocity modulation tube. Here a high Velocity electron beam in formed and focussed and sent down along the glass tube through an i/p Cavity (buncher) field free drift space and o/p Cavity (catther) to a anode. the input and output are taken via resonant Cavities with the aid of Coupling loops.

* Operation :- The apple gate diagram of Klystron amplifier is shown in fig.



The RF signal is to be amplified fed at buncher cavity so these developed a alternative or ac voltage signal across gap A.

The effect of this gap voltage on electron beam is explained by using Apple gate diagram.

At the point B on the input RF cycle the voltage is zero at this instant the electric field across gap A is zero. Hence the electron beam which passes through the gap is uneffected by RF signal. that electron is called reference electron e_R. It travels with unchanged velocity $v_0 = \sqrt{\frac{2eV}{m}}$

At point c of the input RF cycle an electron leaves the gap later than reference electron e_R called the late electron e_L it is subjected to maximum positive RF voltage Hence travels with velocity greater than velocity of reference electron $(v > v_0)$

Illy an early electron e_e that passes through the gap A slightly before the reference electron e_R subjected to max negative field. Hence the early electron travels with decreasing velocity $(v < v_0)$. So this electron falls back and reference electron catch up with the early electron.

Therefore the Velocity of electron beam Varies in accordance With RF input voltage, resulting in velocity modulation of the electron beam.

As result of those actions the electrons in the bunching limit are gradually bunch together.

The pulsating stream of electrons passes through gap B and excite oscillations in the o/p Cavity

The density of electrons passing the gap B vary cyclically With time ie, an electron beam Conta-ins an ac Current

So the drift space Converts the velocity modula-tion into Current modulation

Bunching occurs only once per Cycle Centered around the reference electron With proper design a little RF power applied to the buncher Cavity results in large beam Currents at the cather Cavity With a Considerable power gain.

* performance characteristics:

frequency : 250MHz to 100GHz

power : 10KW - 50KW

power gain : 15db - 70db

* Applications:

1) As power output tubes

* In UHF TV transmitters

* In troposphere Scatter transmitter

* satellite Comm ground stations

* Radars transmitters.

2) As power Oscillator (5-50 GHz)

It is used an klystron amplifier.

* Mathematical analysis:- [Velocity modulation equation]

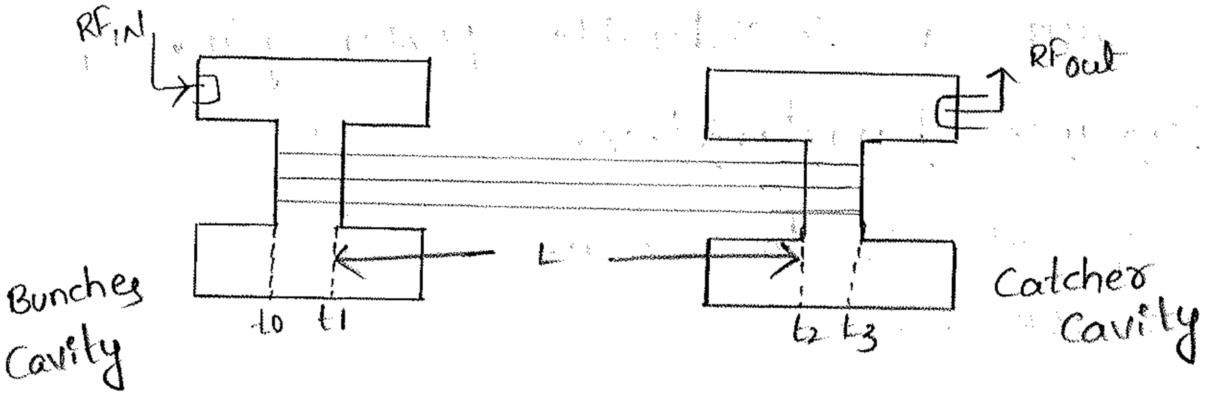
let the dc voltage between Cathode and anode be V_0 and v_0 be the velocity of the electron, l be the drift Space length and i/p RF signal E_0 be amplified by klystron be V_s.

$$v_0 = \sqrt{\frac{2eV_0}{m}} = 0.593 \times 10^{6} \sqrt{V_0} \text{ m/sec}$$

$e = 1.6 \times 10^{-19}$ c

$m = 9.11 \times 10^{-31}$ kg

$$V_s = V_1 \sin \omega t \quad (V_1 << V_0)$$



The energy of the electron at the time of leaving bunching Cavity is given by

$$\frac{1}{2}mv_1^2 = e(V_0 + V_1 \sin\omega t_1)$$

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

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

$$= v_0\left[1 + \frac{V_1}{V_0}\sin\omega t_1\right]^{1/2}$$

$$v_1 = v_0\left[1 + \frac{V_1}{2V_0}\sin\omega t_1\right] \quad \text{— ①}$$

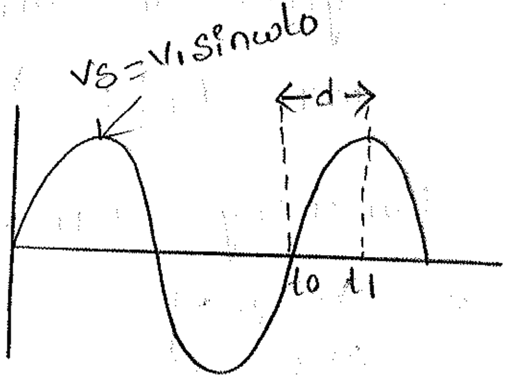
This is equation of velocity modulation

and $\omega t_1 = \omega t_0 + \theta_g$

Where θ_g is the phase angle of the RF i/p voltage during which the electron is accelerated

$$\theta_g = \omega_t = \omega(t_1 - t_0) = \frac{\omega d}{v_0}.$$

* Efficiency :-



Efficiency is given by

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

let at the catcher cavity RF voltage $= V_2 \sin\omega t_2$

The energy given by electron to bunch is

$$= (-e)V_2\sin\omega t_2 = -eV_2\sin\omega t_2$$

The Average energy given to RF field in a cycle

$$P_{av} = \frac{1}{2\pi}\int_{\omega t_1=0}^{\omega t_1=2\pi} (-eV_2 \sin\omega t_2)\, d\omega t_1 \longrightarrow \text{eq ②}$$

In the field free space b/w cavities the transit time for velocity modulated electron is given by

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

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

multiply by ω

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

In above eq'n $\frac{L}{V_0} = T_0$ is the transit time with out RF voltage V_s and $\omega T_0 = \theta_0 = 2\pi N$ is the transit angle with out RF voltage V_s. N is no of transit cycles in drift space

$$\omega T = \theta_0\left[1 - \frac{V_1}{2V_0}\sin\omega t_1\right] \text{ — ③}$$

[The bunching parameter X of klystron is defined as $X = \frac{V_1}{2V_0}\theta_0$]

and proportional to input power ∴ from eq ②

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

$$= -\frac{eV_2}{2\pi}\int_0^{2\pi} \sin\left(\omega t_1 + \theta_0\left(1 - \frac{V_1}{2V_0}\sin\omega t_1\right)\right) d\omega t_1 \quad [\text{from eq ③}]$$

This is Bessel function and it 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 energy transferred is $N P_{av} = -Ne\,V_2 J_1(X)\sin\theta_0$

$Ne = I_0$ the output current

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

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

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

The output power $P_{out(max)} = 0.58\, I_0 V_2$

for $\sin\theta_0 = -1$ $\quad\theta_0 = 2n\pi - \pi/2$

* input power:-

The Input power is basically the dc i/p power is given by

$$\boxed{P_{in} = I_0 V_0}$$

The efficiency is given by

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

V_2 is always less than V_0. So the max efficien -cy is 0.58 or 58%.

Further efficiency in function of transit angle and is max for a $\theta_1 = \theta_0 = -\pi/2$ and zero for $\theta_1 = 2\pi$

for max power transfer the electron gunn anode voltage required is given by $(V_1/V_0)_{max}$

We know that

for max $X = 1.84$

$\theta_0 = 2n\pi - \pi/2$

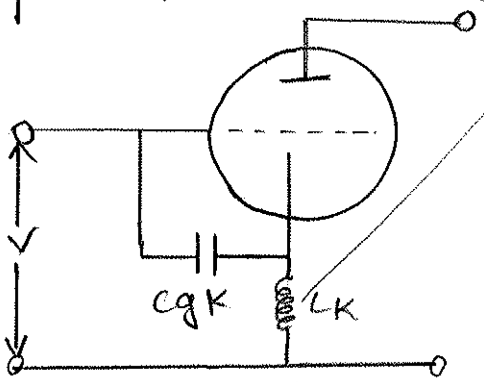
$$X = \frac{V_1}{2V_0}\theta_0$$

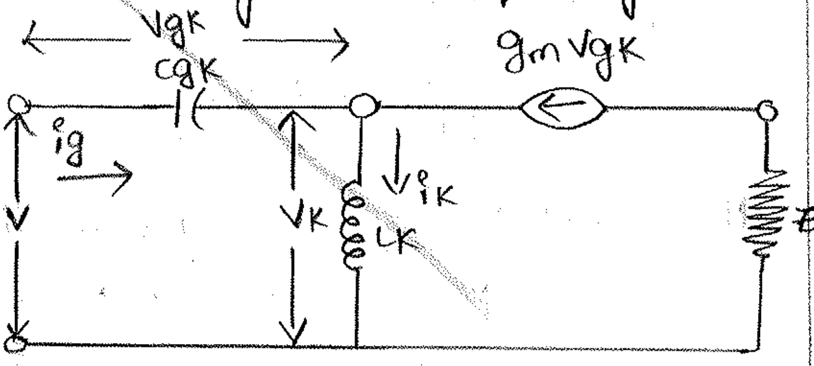
$$\boxed{\left[\frac{V_1}{V_0}\right]_{max} = \frac{2X}{\theta_0} = \left[\frac{3.68}{2n\pi - \pi/2}\right]}$$

* Combined effect of LI, IEC and transit time:-

Assuming that the effect of l_p, l_g, C_{gp} and C_{pK} are negligible. The equivalent Circuit of tube can be shown in figure ⓐ & ⓑ

Now we shall prove that Y_{in} is indirectly proportional to Square of angular frequency.





Applying KVL at input side

$$V = V_{gK} + V_K \rightarrow ①$$

Applying KCL at node K

$$i_K = i_g + g_m V_{gK} \longrightarrow ②$$

But Voltage across the Capacitor

$$V_{gK} = i_g X_{C_{gK}}$$

$$= i_g / j\omega C_{gK}$$

$$\boxed{i_g = j\omega C_{gK} V_{gK}} \longrightarrow ③$$

Voltage across the inductor $V_K = i_K X_{L_K} = j\omega L_K i_K$

$$V_K = j\omega L_K (i_g + g_m V_{gK}) \longrightarrow ④$$

From eq'n ① & ②

$$V = V_{gK} + j\omega L_K (i_g + g_m V_{gK})$$

$$= V_{gK} + j\omega L_K i_g + j\omega L_K g_m V_{gK} \quad [\text{from eq}(3)]$$

$$= V_{gK} + j\omega L_K (j\omega C_{gK} V_{gK}) + j\omega L_K g_m V_{gK}$$

$$V = V_{gK} [1 + j\omega L_K g_m - \omega^2 L_K C_{gK}]$$

$$Y_{in} = \frac{(j\omega C_{gK}}{1 - \omega^2 L_K C_{gK} \left[1 + \frac{j\omega L_K g_m}{1 - \omega^2 L_K C_{gK}}\right]}$$

$$= \frac{j\omega C_{gK}}{(1 - \omega^2 L_K C_{gK})} \left[1 + \frac{j\omega L_K g_m}{1 - \omega^2 L_K C_{gK}}\right]^{-1}$$

$$= \left[\frac{j\omega C_{gK}}{1-\omega^2 L_K C_{gK}}\right]\left[1 - \frac{j\omega L_K g_m}{1-\omega^2 L_K C_{gK}}\right]$$

If we assume $\omega^2 L_K C_{gK} << 1$

$$Y_{in} = j\omega C_{gK}(1 - j\omega L_K g_m)$$

$$\boxed{Y_{in} \approx \omega^2 L_K C_{gK} g_m + j\omega C_{gK}}$$

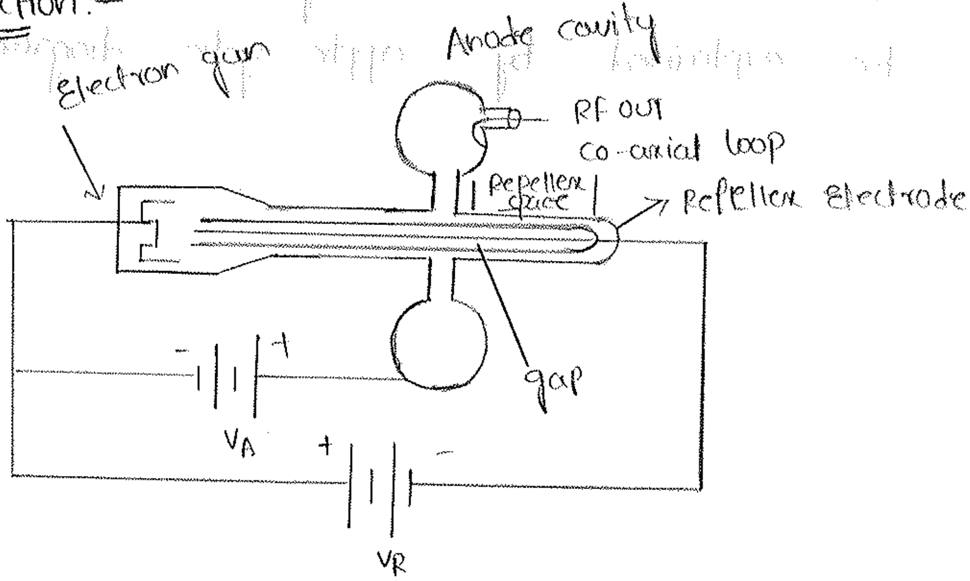
Y_{in} has real and imaginary Components. The real Component is Conductive Component which absorbs power from the Signal Source the amount of which is proportional to Square of frequency.

Then the i/p admittance of the triode ckt is

$$Y_{in} = i_g/V = \frac{j\omega C_{gK} V_{gK}}{V_{gK}[1 + j\omega L_K g_m - \omega^2 L_K C_{gK}]}$$

Reflex klystron :- A reflex klystron is a single cavity variable frequency microwave generator of Low power and Low efficiency.

Construction :-



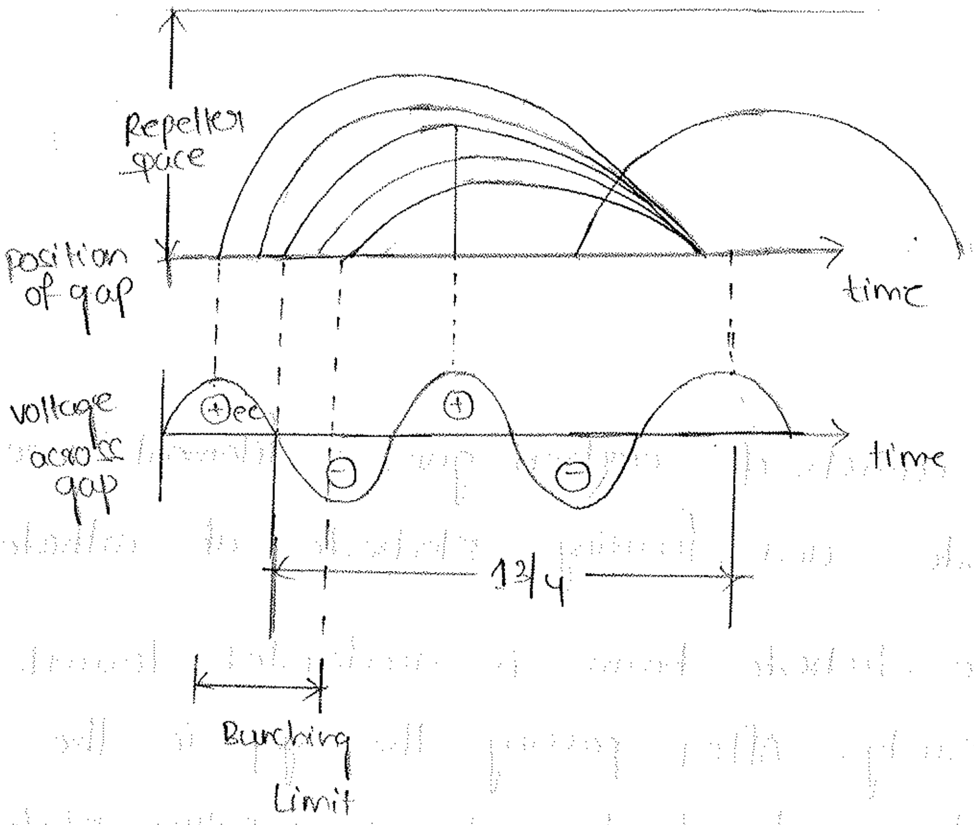
It consists of electron gun, a filament surrounded by cathode and focusing Electrode at cathode

The electrode beam is accelerated towards the anode cavity. After passing the gap in the cavity the electrons travel towards a repeller Electrode which is at high negative potential V_R. The electrons never reach the repeller because of negative field and are returned back to words gap.

Under suitable conditions the electron ~~gave~~ give more more energy to the gap than they took from the gap on their forward journey and oscillation are sustained.

operation:-

Finally assumed that oscillations are setup in the tube due to noise of switching tranciants. These oscillators are sustained by device operation. This can be explained by apple gate diagram.



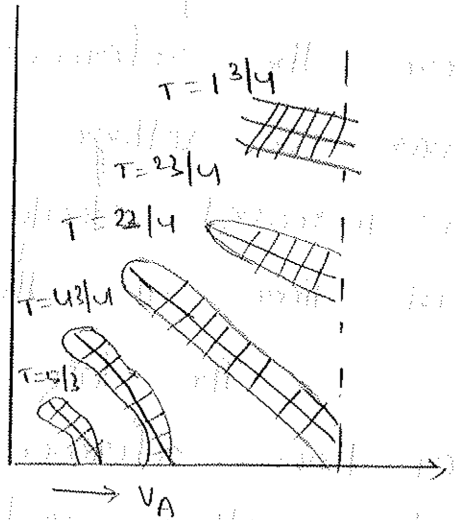
The RF voltage produced across the gap by the cavity oscillations and act on electron beam to cause velocity modulation.

e_R is the reference electron that passes through the gap when gap voltage is zero. Hence it is uneffected by the gap voltage on repeller and return to gap for second time.

operating characteristics

1) Voltage characteristics :-

oscillations can be obtained only for specific combinations of bunch occure only once ~~for~~ per cycle and ~~them~~ bunches from for energy to gap to get sustained oscillations.



In general optimum transit time $T = n + \frac{3}{4}$

The shaded area shows possible combinations and heavy line show optimum combinations. The values N = 1, 2, 3 ..... are corresponds to different modes of reflex klystron the large power is obtained at earlier mode but volt require are also high. which leading to insulation problems and lowers the efficiency. Therefore modes corresponding to n = 2 dx = 3 are most widely used.

Power output and frequency characteristics :-

The mode curves and frequency characteristics are shown in fig. the oscillation freq is devided by freq of resonance of cavity variations of repeller voltage highly changes the frequency. This amounts to electronic tuning of reflex klystron. so reflex klystron used as voltage tuned oscillator or freq mod oscillator.

The early electron e_e that passes through the gap before the reference electron e_R which experiences a max +ve voltage across the gap. Hence it moves with increased velocity and appear at the gap for the second time at the same instant.

The late electron e_l that passes the gap later than reference electron experiences a max negative voltage and moves with retarded velocity. The return time is shorter as penetration into repeller space is less catchup with e_R and e_l forming a bunch.

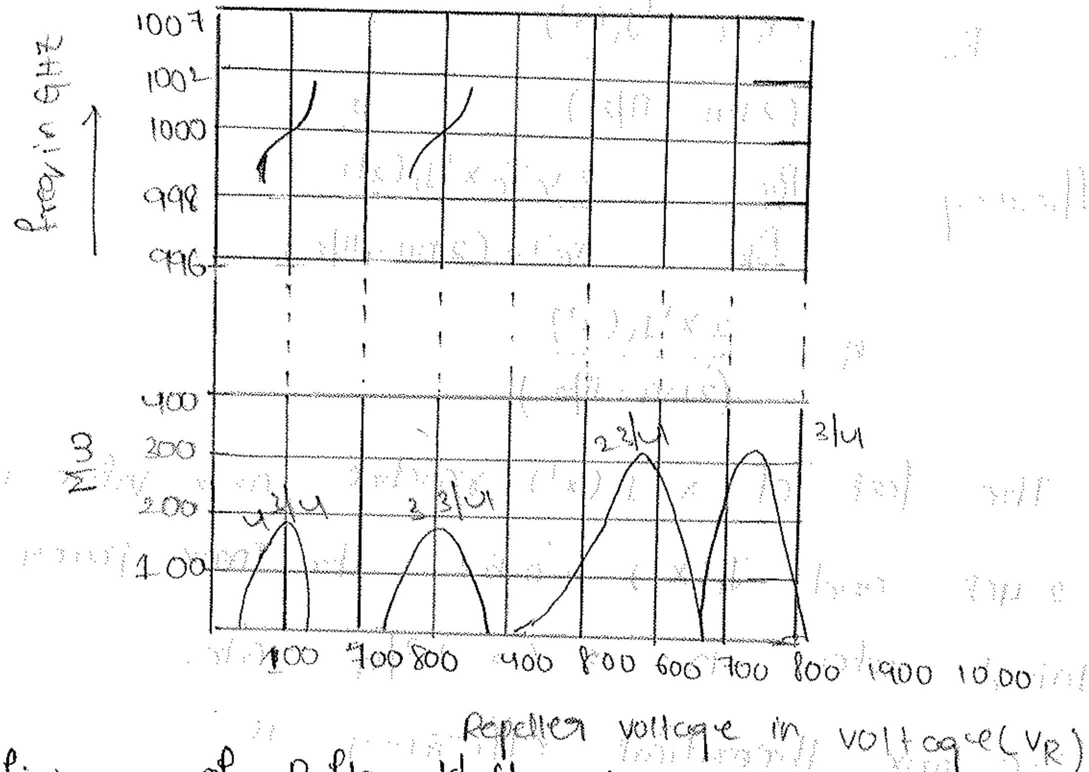
Bunches occur once per cycle centered around the reference electron e_R and these bunches from for max energy to the gap to get sustained oscillations.

For sustained oscillations the time taken by electrons to travel in to repeller space and back to the gap (transit time) must have an optimum value. from the fig optimum transit time for the bunch to arrive at the cavity is $(n+3/4)$ cycle after the beam intially left the cavity.

For max Energy transfer the round strip transit angle is $\omega(t_2-t_1) = \omega T_0 = \theta_0 = 2\pi n - \pi/2 = 2\pi(n-\pi/4)$

$= 2\pi N$

n is any positive integer and $N = n - 1/4$ is mode number.



Efficiency of Reflex klystron :-

In Reflex klystron max power is transferred to to the output when bunched electrons arrive at the cavity DC power supplied by beam voltage V_0 is

$$P_{dc} = V_0 I_0$$

Ac power delivered is

$$P_{ac} = I_0 V_2 J_1(x') \sin\theta' \text{ ——— ①}$$

As current flow in the Reverse direction negative sign becomes positive and V_2 is V_1 being single and same cavity.

$$P_{ac} = I_0 V_1 J_1(x') \quad (\sin\theta' = 1) \text{ ——— ①}$$

Here $x' = \frac{V_1}{2V_0}\theta'$

$$\frac{V_1}{V_0} = \frac{2x'}{(2n\pi - \pi/2)} \text{ ——— ②}$$

sub eqn② in eq①

$$P_{ac} = \frac{2V_0I_0\, x'J_1(x')}{(2n\pi - \pi/2)}$$

$$\text{efficiency} = \frac{P_{ac}}{P_{dc}} = \frac{2V_0I_0\, x'J_1(x')}{V_0I_0\,(2n\pi - \pi/2)}$$

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

The fact of $x'J_1(x')$ reaches max value when $x' = 2.408$ and $J_1(x') = 0.52$. the max power out is obtained when $n = 2$ or $1\,3/4$ mode.

so max theoritical efficiency is

$$\eta_{max} = \frac{2(2.408)(0.52)}{2(\pi)2 - \pi/2} = 22.78$$

The practical value ~~a~~ is around 20%.

Note:- mode number of reflex klystron $N = (n+3/4)$

power output interms repeller voltage

$$P_{out} = \frac{2V_0I_0\, x\, J_1(x')}{(2n\pi - \pi/2)}$$

$$\theta_0 = \omega T_0 = \frac{2ms\omega}{e(V_R + V_0)}\, v_0$$

$$P_{out} = \frac{2I_0V_0\, x'J_1(x')}{2ms\omega V_0} \times (V_R + V_0)e \quad \boxed{v_0 = \sqrt{\frac{2eV}{m}}}$$

$$\frac{I_0V_0\, x'J_1(x')}{\omega s} \times \sqrt{\frac{e}{2mV_0}}$$

For max value of $x'J_1(x) = 1.25$

$$P_{max} = \frac{1.25\, I_0 V_0 (V_R - V_0)}{\omega_c} \times \sqrt{\frac{e}{2mV_0}}$$

Relation b/w Repeller voltage (V_R) and accelerated voltage (V_0) :-

we know $\theta_0' = \frac{-2mS\omega}{e(V_R - V_0)}$ (or)

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

$$v_0^2 = \frac{+e^2(V_R - V_0)^2}{4m^2S^2\omega^2}\theta_0^2$$

we know that

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

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

$$= \frac{m}{2e}\frac{e^2(V_R - V_0)^2}{4m^2\omega^2S^2}$$

$$\frac{V_0}{(V_R - V_0)^2} = \frac{m}{2e}\frac{e^2}{4m^2\omega^2S^2}(2n\pi - \pi/2)^2$$

$$\frac{V_0}{(V_R - V_0)^2} = \frac{1}{8}\frac{e}{m\omega^2S^2}(2n\pi - \pi/2)^2$$

Expression for change in freq due to repeller voltage (Electronic tuning of Reflex klystron)

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

Diff V_R with respect to ω

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

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

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

$$= \sqrt{\frac{8mV_0}{e}}\,\frac{s}{(2ms - \frac{\pi}{2})}$$

$$\frac{dV_R}{df} = \frac{2\pi s}{2n\pi - \pi/2}\sqrt{\frac{8mV_0}{e}}$$

This is very useful relationship for electronic tuning of reflex klystron. If repeller voltage (usually 2kV) is varied by even 2% frequency will very quide considerably.