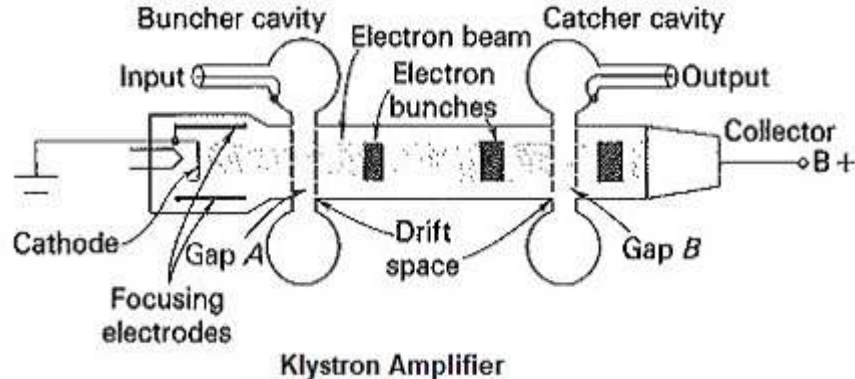


Klystron in Microwave Engineering

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A Klystron is a velocity modulated tube, in which the velocity modulation process produces a density modulated stream of electrons. Figure shows the '2-cavity klystron amplifier'. It is distinguished that a high velocity electron beam is created. It is a high positive potential with respect to cathode. Magnetic focusing is used here.



Klystron Amplifier

A 2-cavity klystron amplifier comprises of a cathode focusing, electrodes, two buncher grids divided by an extremely small space appearing a gap A, two catcher network with a small gap B trail by a collector. The input and output are taken from the tube via resonant cavities. The separation between buncher grids and catcher grids is called, 'drift space'. The electron beam passes gap A in the buncher cavity to which RF signal to be amplified is applied and is then allowed to drift freely without any interference from RF fields until it reaches the gap B in the output or catcher cavity.

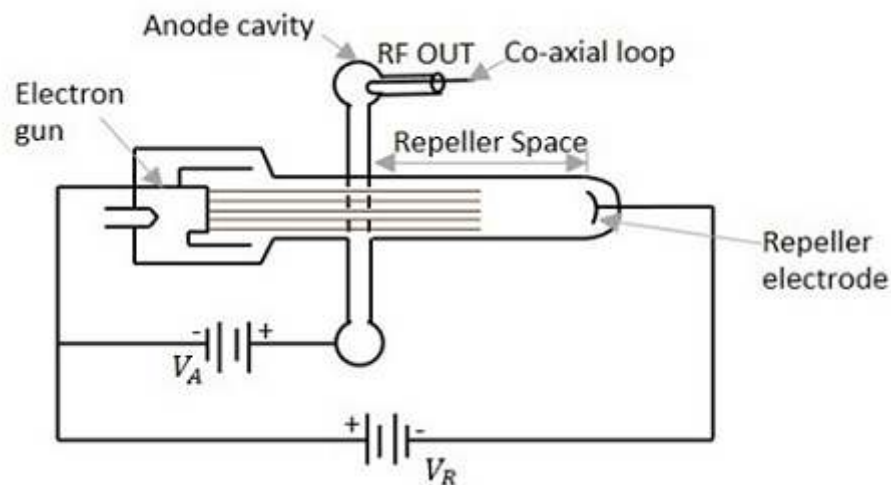
The first grid controls the number of electrons in the electron beam and serves to focus the beam. The velocity of electron in the beam is determined by the beam accelerating potential. On leaving the region of first grid the electrons pass through the grids of buncher cavity. The grids of the cavity allow the electrons to pass through, but confine the magnetic fields within the cavity. The space between the grids is called 'inter-action space'. When electrons travel through this space, they are subjected to RF potentials at a frequency determined by the cavity reasonably frequency or the input frequency. The amplitude of this RF potential between the grids is determined by the amplitude of the incoming signal in case of the amplifier, or by the amplitude of the feedback signal from the second cavity if used as in oscillator. Then oscillations will be excited in the second cavity which is of a power much higher than in the buncher cavity, so that a large output can be taken.

Applications:

A multicavity klystron can be used as a medium or high power amplifier in the UHF and microwave ranges, for both continuous and pulsed operations. The power ranges vary from 10kW to 25MW. The power gain ranges from 30dB to 60dB.

Reflex Klystron Oscillator:

The Reflex Klystron Oscillator is a low power microwave oscillator generating power in the range of 10 -500 MW. The output frequency range of the oscillator is in the range of 1 to 25 GHz. The efficiency of Reflex Klystron is about 20 – 30%. This type of oscillator is mainly used in microwave laboratories for microwave measurements and as local oscillators in commercial and military radars. The Reflex Klystron Oscillator theory is explained below.



Reflex klystron is a single cavity klystron that can be used as low power microwave oscillator. Due to the DC voltage in the cavity, a Radio Frequency (RF) noise is generated. The electron beam injected from the cathode is velocity modulated by the cavity gap voltage. Electrons which encounter the positive half cycle of the RF field will get accelerated. Those electrons which encounter zero RF field will pass with unchanged velocity (constant velocity). Electrons which encounter negative half cycles will be retarded. Some of the accelerated electrons enter the 'repeller space' with greater velocities and these electrons are retarded by the retarding field in the repeller space. Since the repeller space is at negative potential, the electrons entering the repeller space are repelled back. These electrons give up Kinetic Energy into the field on their return journey. The electrons are finally collected by walls of the cavity by keeping unity gain and phase-shift of 2π sustained oscillations are obtained.

Velocity Modulation:

The uniform velocity with which the electrons enter the cavity is given by,
$$V_0 = \sqrt{(2eV_0/m)}$$

Where, e – charge of electron
 m – mass of electron.
 Substitute values of e and m .

$$V_o = 0.596 \times 10^6 \sqrt{V_o} \text{ m/s} \text{ ----- } 1$$

The velocity with which the electrons leave the cavity is given by,

$$V(t_1) = V_o[1 + \beta_1 V_1/V_o \sin(\omega t_1 - \theta_g/2)]$$

The electric field inside the cavity is given by,

$$E = [V_r + V_o + V_1 \sin(\omega t_1)]/L$$

where, V_r – repeller voltage

V_o – output voltage/DC gain beam voltage.
 L – Length of drift space

If $V_1 \sin(\omega t_1)$ is less than $V_r + V_o$, then

$$E = (V_r + V_o)/L \text{ ----- } (3)$$

The force of electron is given by
 $F = -eE$

Substituting for E

$$\text{We have, } F = -e((V_r + V_o)/L) \text{ ----- } (4)$$

$$F = ma = m(d^2z/dt^2) \text{ ----- } (5)$$

Equating eq (4) and (5)

$$m(d^2z/dt^2) = -e((V_r + V_o)/L)$$

$$d^2z/dt^2 = -e((V_r + V_o)/Lm)$$

$$dz/dt = -e((V_r + V_o)/Lm)(t-t_1) + K_1$$

The above equation represents the velocity change taking place inside the cavity. The velocity change is obtained as a ratio of change in distance to change in time where z is the distance.

Output Power and Efficiency:

For the electron beam to generate maximum amount of energy, the returning electron beam should pass the cavity gap with less retardation. Thus, for maximum energy transfer the DC transit angle is given by,

$$\Theta_0^1 = \omega(t_2 - t_1) = \omega T_o'$$

$$\Theta_0^1 = 2N\pi$$

Where, N = the no: of modes
 $N = n - 1/4$

Therefore $\Theta_0^1 = 2\pi(n - 1/4)$
 $= 2\pi n - \pi/2$ ----- (1)

The magnitude of current in the cavity is given by,

$$I_2 = 2I_o\beta_i J_1(x')$$
 ----- (2)

The DC power supplied is given by,

$$P_{dc} = V_o I_o$$
 ----- (3)

The AC power supplied is given by,

$$P_{ac} = V_1 I_2 / 2$$

Substituting for I_2 from eq(2)
 $P_{ac} = V_1 I_o \beta_i J_1(x')$ ----- (4)

Let, the bunching parameter of the reflex klystron is given by
 $x' = \beta_i V_1 \theta_o' / 2V_o$

Therefore, $V_1 = 2V_o x' / \beta_i \theta_o'$

Substituting for θ_o' from eq (1)
 $V_1 = 2V_o x' / \beta_i (2\pi n - \pi/2)$ ----- (5)

Substitute eq (5) in (4)

$$P_{ac} = 2V_o x' I_o J_1(x') / (2\pi n - \pi/2)$$
 ----- (6)

The efficiency of the klystron is given by,

$$\eta = P_{ac} / P_{dc}$$

Substituting values from eq (6) and (3)

$$\eta = [2V_o x' I_o J_1(x') / (2\pi n - \pi/2)] \times 1 / V_o I_o$$

$$\eta = [2 x' J_1(x') / (2\pi n - \pi/2)]$$

For a given beam voltage, V_o

The repeller voltage, V_r is related to number of modes as,

$$V_o/(V_r + V_o)^2 = e/m (2\pi n - \pi/2)^2/8\omega^2 L^2$$

Admittance:

The admittance of the klystron is the ratio of induced current to induced voltage.

$$\text{ie, } Y_e = i_2/V_2$$

$$\text{Where, } i_2 = 2I_o\beta_i J_1(x')e^{-j\theta_o'}$$

$$V_2 = I_2 R_{sh}$$

$$= 2 x'V_o e^{-j\pi/2} / \beta_i(2\pi n - \pi/2)$$

Substitute I_2 and V_2 ,

$$Y_e = (2I_o\beta_i J_1(x')e^{-j\theta_o'}) (\beta_i(2\pi n - \pi/2)) / 2 x'V_o e^{-j\pi/2}$$
$$= I_o\beta_i^2 J_1(x')e^{-j\theta_o'}(2\pi n - \pi/2) / x'V_o e^{-j\pi/2}$$

Hence the admittance of the Reflex Klystron is obtained as:

$$Y_e = I_o\beta_i^2 J_1(x')e^{j(\pi/2 - \theta_o')} (2\pi n - \pi/2) / x'V_o$$

Magnetron Oscillators:

A Magnetron Oscillator is used to generate high microwave power required in radar and communication systems. Magnetrons are cross field tubes in which the magnetic field and electric field are perpendicular to each other. All magnetrons consist of some form of anode and cathode operated in DC magnetic field which is perpendicular to DC electric field. Due to this cross field, electrons emitted from cathode moved in curved paths. If the magnetic field is strong enough the electrons will not arrive at the anode, but return to cathode itself. Thus the anode current is cut off. Magnetrons can be classified into three. They are

1. Split anode magnetron:

This type of magnetron uses negative resistance.

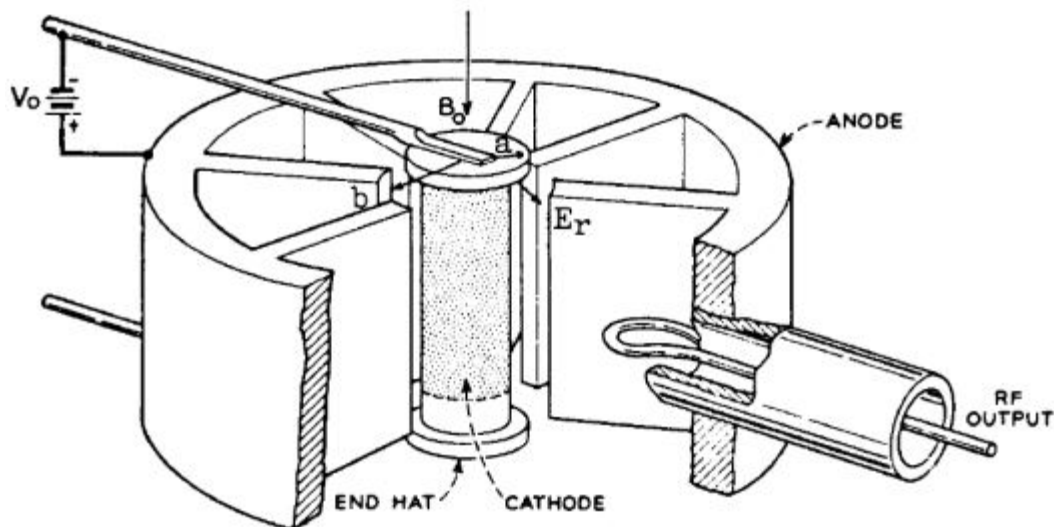
2. Cyclotron frequency magnetron:

This magnetron operates under the influence of synchronization between AC components of electric field and periodic oscillations of electrons in the direction parallel to the electric field.

3. Travelling wave magnetron:

This type of magnetron depends on the interactions of electrons with travelling electromagnetic field.

Cylindrical Magnetron Derivation:



Schematic Diagram of Cylindrical Magnetron

B_0 - Flux Density

a - radius of cathode cylinder

b - radius of anode cylinder

Equation of Electron Motion or Hull cut off Voltage equation:

A charged particle in motion in a magnetic field of flux density B , experiences a force that is proportional to the charge, velocity, flux density and sine of angle between velocity and magnetic flux. The general equation for the motion of electron in terms of cylindrical co-ordinates is given as,

$$r^2(d\Phi/dt) = \frac{1}{2}\omega_c r^2 + \text{constant} \text{ ----- (1)}$$

Where ω_c is the cyclotron angular frequency given by,

$$\omega_c = eB_z/m$$

e – charge of electron

B_z – magnetic flux density

M – mass of electron

Let, $r = a$ and $d\Phi/dt = 0$

Therefore, Equation (1) becomes

$$\frac{1}{2}\omega_c a^2 + \text{Constant} = 0$$

$$\text{Constant} = -\frac{1}{2}\omega_c a^2 \text{ ----- (2)}$$

Substitute equation (2) in (1)

$$r^2(d\Phi/dt) = \frac{1}{2}\omega_c r^2 - \frac{1}{2}\omega_c a^2 = \frac{1}{2}\omega_c (r^2 - a^2)$$

$$d\Phi/dt = \omega_c (r^2 - a^2)/2r^2 = \frac{1}{2}\omega_c (1 - (a^2/r^2)) \text{ ----- (3)}$$

The KE of electrons is given by,

$$\frac{1}{2}mv^2 = eV$$

$$v^2 = 2eV/m$$

considering r and Φ components of electron velocity, the above equation can be represented as,

$$v_r^2 + v_\phi^2 = 2eV/m$$

$$(dr/dt)^2 + (r d\Phi/dt)^2 = 2eV/m \text{ ----- (4)}$$

Let $r = b$

$$V = V_0$$

$$dr/dt = 0$$

Therefore the above equation (4) becomes,

$$(b \, d\Phi/dt)^2 = 2eV_o / m \text{ ----- (5)}$$

Substituting $d\Phi/dt$ from eq (3)

$$b^2(\omega_c/2 (1 - (a^2/r^2)))^2 = 2eV_o / m$$

Substituting $r = b$

$$b^2(\omega_c (1 - (a^2/b^2)))^2 = 2eV_o / m$$

$$b^2\omega_c/4(1 - (a^2/b^2))^2 = 2eV_o / m$$

$$b^2\omega_c^2(1 - (a^2/b^2))^2 = 8eV_o / m$$

Substituting $\omega_c = eB_z/m$

$$b^2(eB_z/m)^2(1 - (a^2/b^2))^2 = 8eV_o / m$$

$$b^2e^2/m^2 (1 - (a^2/b^2))^2 B_z^2 = 8eV_o / m$$

$$B_z = \sqrt{\frac{8m^2 V_o}{e b^2 (1 - (a/b)^2)^2}}$$

This magnetic field intensity is known as **cut off flux density**, B_{oc}

$$B_{oc} = \sqrt{\frac{8m^2 V_o}{e b^2 (1 - (a/b)^2)^2}}$$

$$V_{oc} = b^2 e B_z^2 (1 - (a/b)^2)^2 / 8m$$

This equation is known as '**Hull cut-off voltage equation**'

Cyclotron Angular Frequency:

The cyclotron angular frequency of cylindrical magnetron is given by,

$$\omega_c = eB/m$$

The period of oscillation is given by,

$$T = 2 \pi / \omega_c$$

$$T = 2 \pi m / eB$$

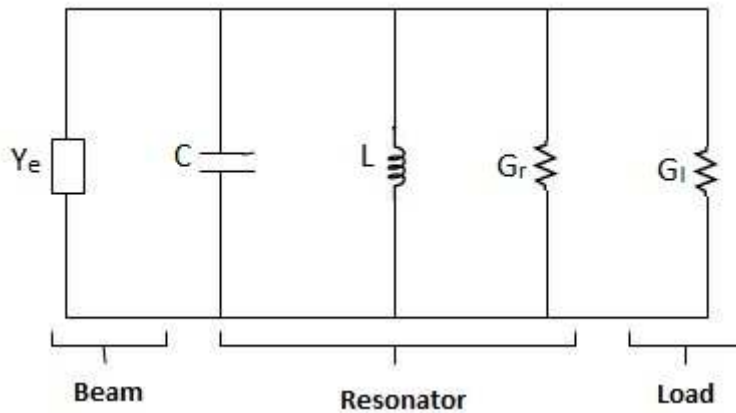
The phase shift is given by,

$$\Phi = 2 \pi m / N$$

Where, N is the number of cycles.

Output Power and Efficiency:

The efficiency and output power of the magnetron depend on the structure and power supply. The equivalent circuit of magnetron is,



Y_e – admittance

C – Capacitance

L – Inductance

G_r – Resonator Conductance

G_l – Load Conductance

The unloaded quality factor is given by,

$$Q_{un} = \omega_0 C / G_r$$

The loaded quality factor is given by,

$$Q_l = \omega_0 C / G_r + G_l$$

The external quality factor,

$$Q_{ext} = \omega_0 C / G_l$$

The circuit efficiency, $\eta_c = 1 / (1 + (Q_{ext} / Q_{un}))$

Electronic efficiency, $\eta_e = (V_o I_o - P_{lost}) / V_o I_o$

Where V_o – Anode Voltage

I_o – Anode Current or Beam Current

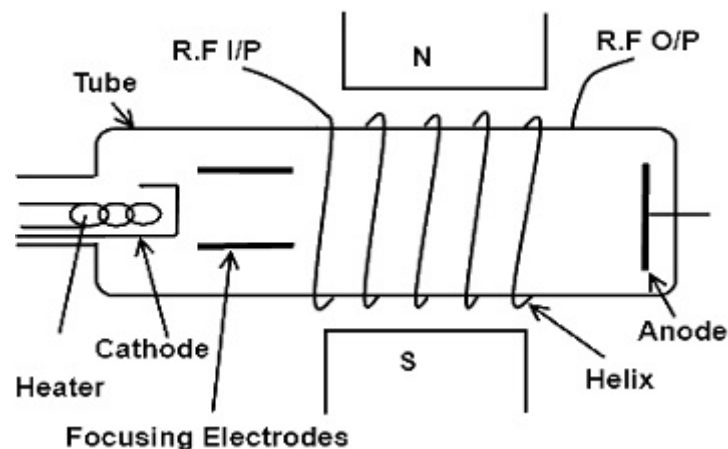
P_{lost} – Power lost in the anode.

Travelling Wave Tube (TWT)

TWT is a high gain, low noise, wideband microwave amplifier. They work on the principle of interaction between electron beam and RF field. In TWT, slow wave structures are used instead of resonant cavities as in Klystrons.

Working Principle

TWT has an electron gun which produces and accelerates the electron beam along the axis of the tube. Surround magnet provides a magnetic field along the axis of tube to focus the electron beam. The slow wave structure at the centre of the tube provides a low impedance transmission path for the RF energy within the tube. The applied input signal which is to be amplified propagates along the slow wave structure. It produces an electric field at the centre of the helix directed along the axis. When the electron beam enters the tube the axial electric field and electron beam are interacted. The electrons entering the slow wave structures at zero electric field are not affected. Those entering at accelerating field are accelerated and those entering at retarding field are decelerated. Thus, velocity modulation takes place and electrons are bunched together and are collected at the collector. The microwave energy of electrons is transferred to slow wave structure and thus the signal is amplified.



Slow Wave Structures:

It reduces the velocity of the wave so that electron beam efficiently interacts with it. They are non resonant periodic circuits. In a normal resonant circuit as the operating frequency is increased both the inductance and capacitance of the resonant circuit must be decreased to maintain the resonance at the operating frequency. This limits the gain and reduces the output. Slow wave Structures compensate this limitation and produces large output over a wide bandwidth.

Various types of Slow wave structures are,

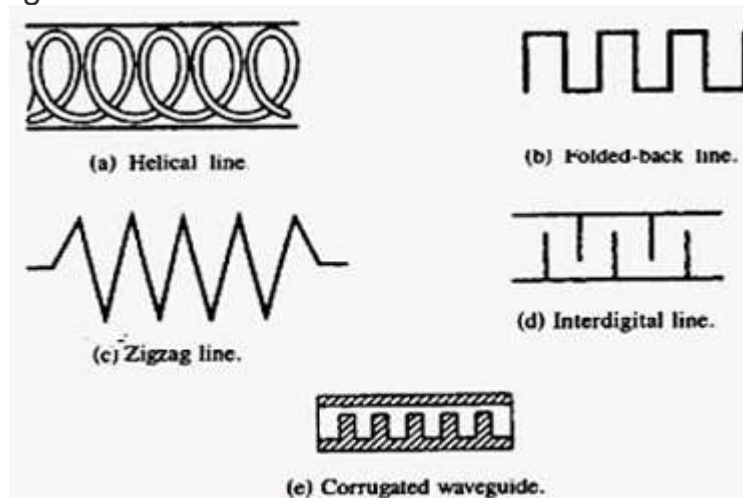
Helical Line

Folded Back Line

Zig Zag Line

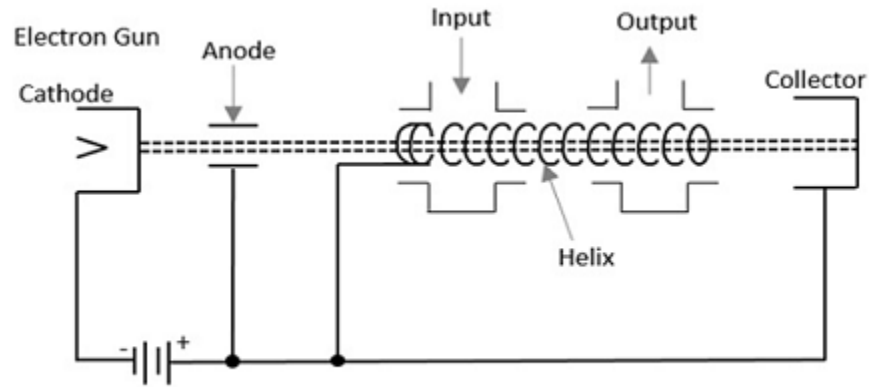
Inter digital line

Corrugated waveguide



Helix Travelling Wave Tube (Helix TWT):

The TWT contains an electron gun which produces and accelerates the electron beam along the axis of the tube. The surrounding magnet provides a magnetic field along the axis of the tube to focus the electrons into a straight beam. A longitudinal helix slow wave structure is placed at the center of the tube which provides low impedance transmission path. The RF input and output are coupled on to and removed from the helix by directional couplers. The travelling wave tube is designed with helix delay structure to slow down the wave below or equal to the speed of electrons. The electrons of the beam are accelerated by interacting with positive value of the electric field through velocity modulation. This result in amplification and the electrons give up energy to the travelling wave. Thus, the energy of travelling wave is increased.



Schematic Electrode Arrangement in TWT

Amplification Process in TWT:

The phase shift of the fundamental wave on the helical slow wave structure is given by the equation,

$$\theta_0 = B_z L$$

where, B_z – Phase constant
 which is defined as $B_z = \omega/V_p$
 L is the period of the signal.

The equation for motion of electron is given by,

$$m(dv/dt) = -eE_1 \sin(\omega t - B_z z) \text{ ----- (1)}$$

Let the velocity of electron be defined as,

$$v = v_0 + v_e \cos(\omega_e t + \theta_e)$$

$$\text{Therefore } dv/dt = -v_e \sin(\omega_e t + \theta_e) \omega_e \text{ ----- (2)}$$

Sub eq (2) in (1)

$$m v_e \sin(\omega_e t + \theta_e) \omega_e = e E_1 \sin(\omega t - B_z z) \text{ ----- (3)}$$

v_e is the magnitude of velocity fluctuation, ω_e is the angular velocity
 θ_e – Phase angle fluctuation

Let, the distance 'z' travelled by the electron is defined as,

$$z = v_0(t - t_0) \text{ ----- (4)}$$

Where, v_0 is the 'dc electron velocity'

Substitute eq (4) in (3)

$$\begin{aligned} m v_e \omega_e \sin(\omega_e t + \theta_e) &= e E_1 \sin(\omega t - B_z v_o(t - t_o)) \\ &= e E_1 \sin(\omega t - B_z v_o t - B_z v_o t_o) \end{aligned}$$

Equating LHS and RHS

$$\text{we get, } m v_e \omega_e = e E_1$$

Therefore,

$$\mathbf{v_e = eE_1/m\omega_e}$$

That is, the magnitude of velocity fluctuation is directly proportional to the magnitude of electric field, E_1 .

$$\text{Here, } \omega_e = \omega - B_z v_o$$

$$\omega = B_z v_p - B_z v_o$$

$$\omega_e = B_z (v_p - v_o)$$

where, v_p – axial velocity.

I.e., the angular velocity, ω_e is proportional to difference between axial and dc velocities.