Microwave Engineering

UNIT-4

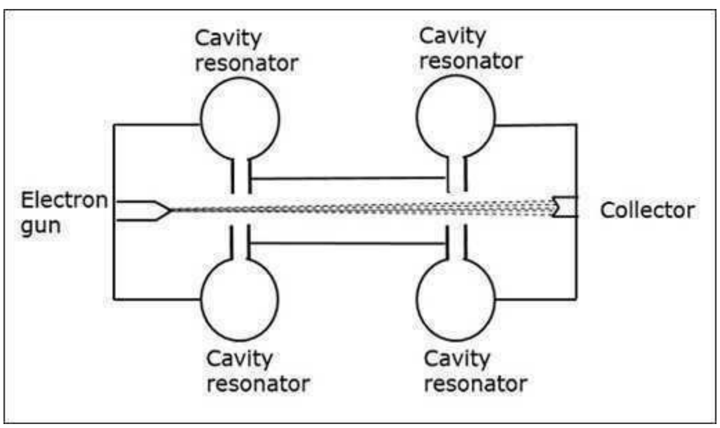
Microwave Vacuum Tube Devices

Interaction of electron beam with electromagnetic field, power transfer condition. Principles of working of two cavity and Reflex Klystrons, arrival time curve and oscillation conditions in reflex klystrons, mode- frequency characteristics. Effect of repeller voltage variation on power and frequency of output. Principle of working of magnetrons. Electron dynamics in planar and cylindrical magnetrons, Cutoff magnetic field, Resonant cavities in magnetron, Π-mode operation Mode separation techniques, Rising sun cavity and strapping. Principle of working of TWT amplifier. Slow wave structures, Approximate gain relationship in forward wave TWT.

Two Cavity Cavity Klystron Oscillator

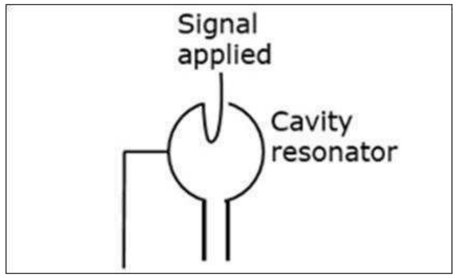
For the generation and amplification of Microwaves, there is a need of some special tubes called as Microwave tubes. Of them all, Klystron is an important one.

The essential elements of Klystron are electron beams and cavity resonators. Electron beams are produced from a source and the cavity klystrons are employed to amplify the signals. A collector is present at the end to collect the electrons. The whole set up is as shown in the following figure.



The electrons emitted by the cathode are accelerated towards the first resonator. The collector at the end is at the same potential as the resonator. Hence, usually the electrons have a constant speed in the gap between the cavity resonators.

Initially, the first cavity resonator is supplied with a weak high frequency signal, which has to be amplified. The signal will initiate an electromagnetic field inside the cavity. This signal is passed through a coaxial cable as shown in the following figure.

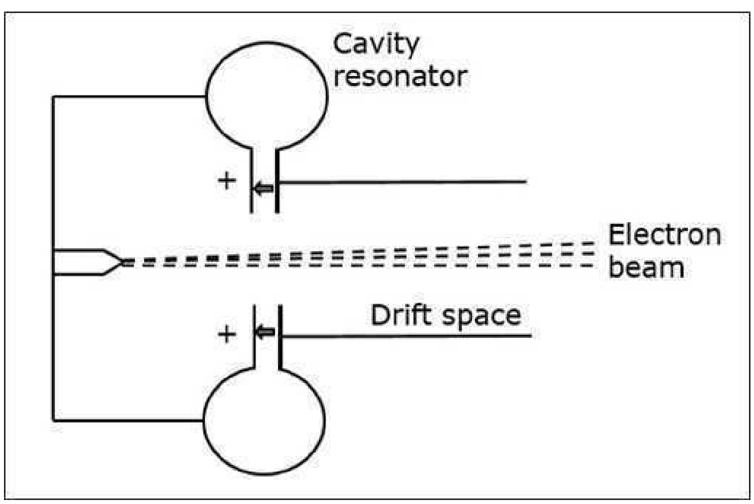


Due to this field, the electrons that pass through the cavity resonator are modulated. On arriving at the second resonator, the electrons are induced with another EMF at the same frequency. This field is strong enough to extract a large signal from the second cavity.

Working of Klystron

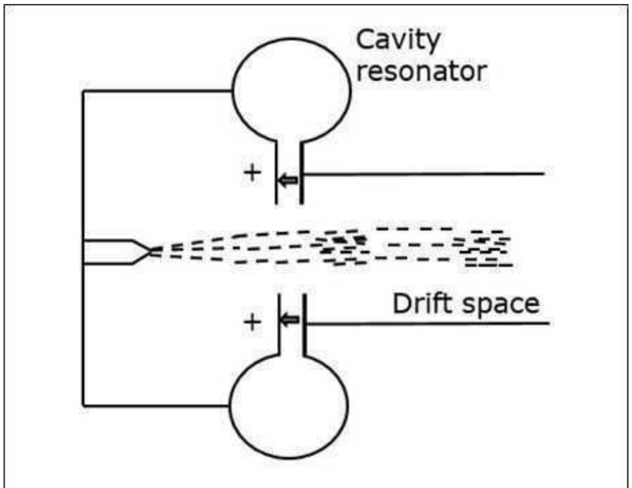
To understand the modulation of the electron beam, entering the first cavity, let's consider the electric field. The electric field on the resonator keeps on changing its direction of the induced field. Depending on this, the electrons coming out of the electron gun, get their pace controlled.

As the electrons are negatively charged, they are accelerated if moved opposite to the direction of the electric field. Also, if the electrons move in the same direction of the electric field, they get decelerated. This electric field keeps on changing, therefore the electrons are accelerated and decelerated depending upon the change of the field. The following figure indicates the electron flow when the field is in the opposite direction.



While moving, these electrons enter the field free space called as the drift space between the resonators with varying speeds, which create electron bunches. These bunches are created due to the variation in the speed of travel.

These bunches enter the second resonator, with a frequency corresponding to the frequency at which the first resonator oscillates. As all the cavity resonators are identical, the movement of electrons makes the second resonator to oscillate. The following figure shows the formation of electron bunches.



Formation of electron bunches

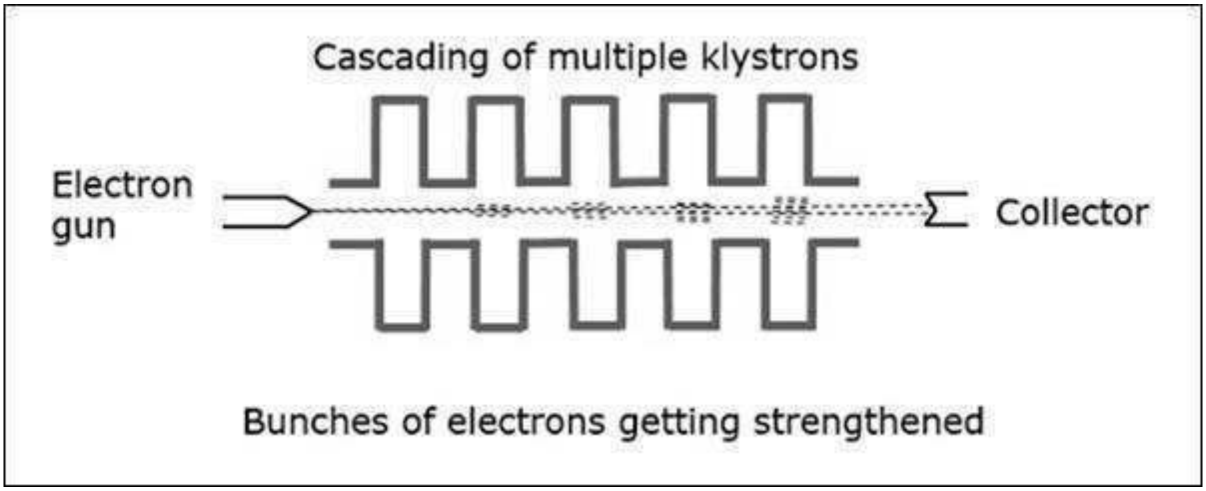
The induced magnetic field in the second resonator induces some current in the coaxial cable, initiating the output signal. The kinetic energy of the electrons in the second cavity is almost equal to the ones in the first cavity and so no energy is taken from the cavity.

The electrons while passing through the second cavity, few of them are accelerated while bunches of electrons are decelerated. Hence, all the kinetic energy is converted into electromagnetic energy to produce the output signal.

<u>Multicavity Klystron Amplifier</u>

Amplification of such two-cavity Klystron is low and hence multi-cavity Klystrons are used.

The following figure depicts an example of multi-cavity Klystron amplifier.



With the signal applied in the first cavity, we get weak bunches in the second cavity. These will set up a field in the third cavity, which produces more concentrated bunches and so on. Hence, the amplification is larger.

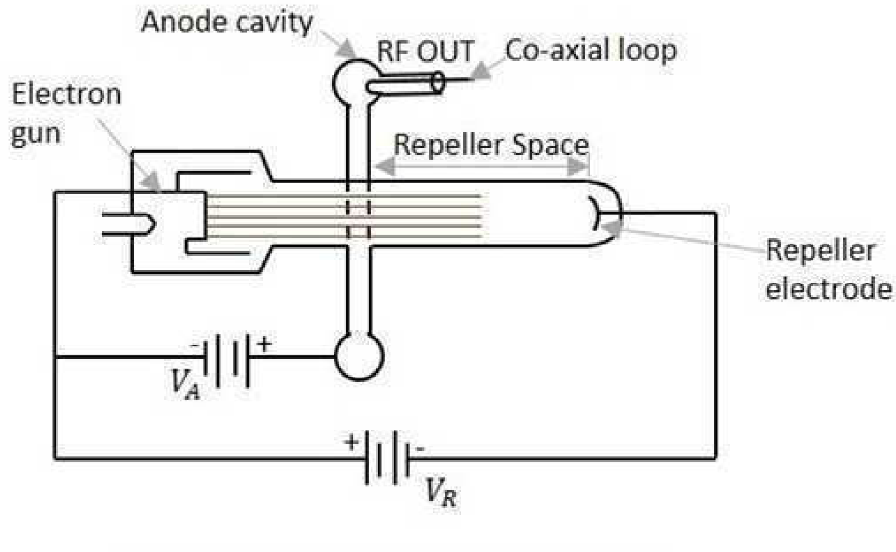
Reflex Klystron

This microwave generator, is a Klystron that works on reflections and oscillations in a single cavity, which has a variable frequency.

Reflex Klystron consists of an electron gun, a cathode filament, an anode cavity, and an electrode at the cathode potential. It provides low power and has low efficiency.

Construction of Reflex Klystron

The electron gun emits the electron beam, which passes through the gap in the anode cavity. These electrons travel towards the Repeller electrode, which is at high negative potential. Due to the high negative field, the electrons repel back to the anode cavity. In their return journey, the electrons give more energy to the gap and these oscillations are sustained. The constructional details of this reflex klystron is as shown in the following figure.



Constructional details of Reflex Klystron

It is assumed that oscillations already exist in the tube and they are sustained by its operation. The electrons while passing through the anode cavity, gain some velocity.

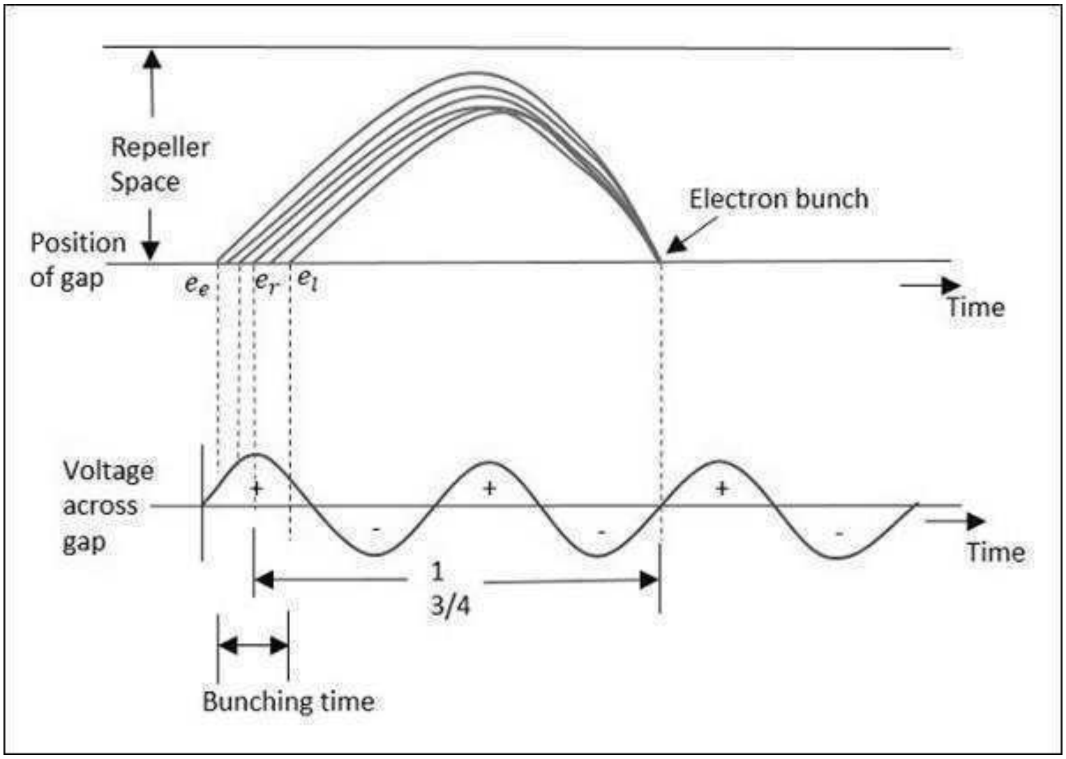
Operation of Reflex Klystron

The operation of Reflex Klystron is understood by some assumptions. The electron beam is accelerated towards the anode cavity.

Let us assume that a reference electron e_r crosses the anode cavity but has no extra velocity and it repels back after reaching the Repeller electrode, with the same velocity. Another electron, let's say e_e which has started earlier than this reference electron, reaches the Repeller first, but returns slowly, reaching at the same time as the reference electron.

We have another electron, the late electron e_l, which starts later than both e_r and e_e, however, it moves with greater velocity while returning back, reaching at the same time as e_r and e_e.

Now, these three electrons, namely e_r, e_e and e_l reach the gap at the same time, forming an electron bunch. This travel time is called as transit time, which should have an optimum value. The following figure illustrates this.



The anode cavity accelerates the electrons while going and gains their energy by retarding them during the return journey. When the gap voltage is at maximum positive, this lets the maximum negative electrons to retard.

The optimum transit time is represented as

T=n+3/4

Where n is an integer

This transit time depends upon the Repeller and anode voltages.

Applications of Reflex Klystron

Reflex Klystron is used in applications where variable frequency is desirable, such as −

- Radio receivers
- Portable microwave links
- Parametric amplifiers
- Local oscillators of microwave receivers
- As a signal source where variable frequency is desirable in microwave generators.

Travelling Wave Tube

Travelling wave tubes are broadband microwave devices which have no cavity resonators like Klystrons. Amplification is done through the prolonged interaction between an electron beam and Radio Frequency (RF) field.

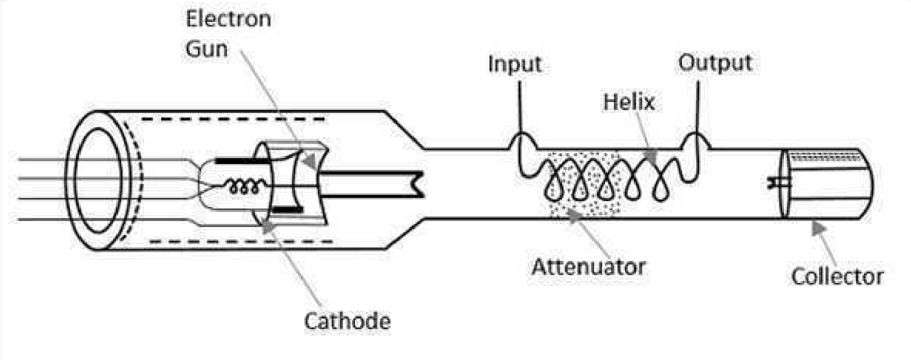
Construction of Travelling Wave Tube

Travelling wave tube is a cylindrical structure which contains an electron gun from a cathode tube. It has anode plates, helix and a collector. RF input is sent to one end of the helix and the output is drawn from the other end of the helix.

An electron gun focusses an electron beam with the velocity of light. A magnetic field guides the beam to focus, without scattering. The RF field also propagates with the velocity of light which is retarded by a helix. Helix acts as a slow wave structure. Applied RF field propagated in helix, produces an electric field at the center of the helix.

The resultant electric field due to applied RF signal, travels with the velocity of light multiplied by the ratio of helix pitch to helix circumference. The velocity of electron beam, travelling through the helix, induces energy to the RF waves on the helix.

The following figure explains the constructional features of a travelling wave tube.



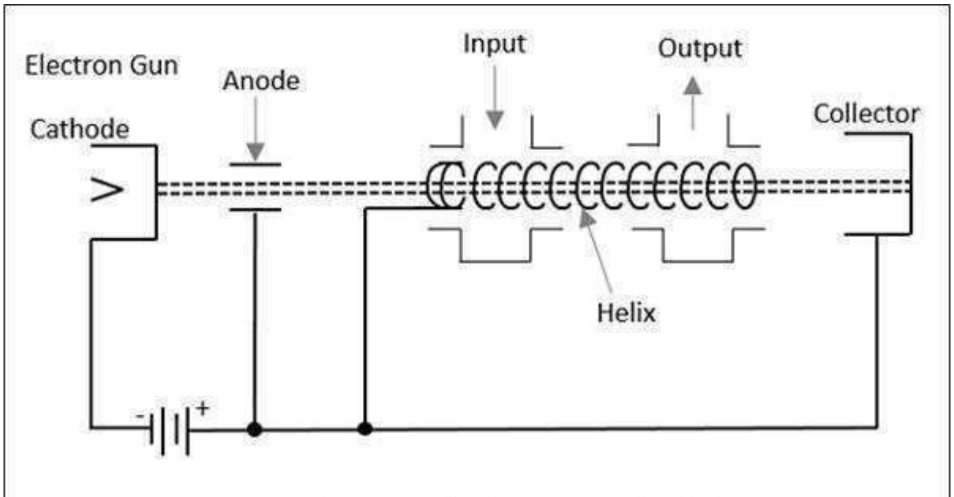
Physical construction of TWT

Thus, the amplified output is obtained at the output of TWT. The axial phase velocity Vp is represented as

$$V_p = V_c(\text{Pitch}/2\pi r)$$

where r is the radius of the helix. As the helix provides least change in Vp phase velocity, it is preferred over other slow wave structures for TWT. In TWT, the electron gun focuses the electron beam, in the gap between the anode plates, to the helix, which is then collected at the collector. The following figure explains the electrode arrangements in a travelling wave tube.

Electrode Arrangements



Schematic Electrode Arrangement in TWT

Operation of Travelling Wave Tube

The anode plates, when at zero potential, which means when the axial electric field is at a node, the electron beam velocity remains unaffected. When the wave on the axial electric field is at positive antinode, the electron from the electron beam moves in the opposite direction. This electron being accelerated, tries to catch up with the late electron, which encounters the node of the RF axial field.

At the point, where the RF axial field is at negative antinode, the electron referred earlier, tries to overtake due to the negative field effect. The electrons receive modulated velocity. As a cumulative result, a second wave is induced in the helix. The output becomes larger than the input and results in amplification.

Applications of Travelling Wave Tube

- There are many applications of a travelling wave tube.
- TWT is used in microwave receivers as a low noise RF amplifier.
- TWTs are also used in wide-band communication links and co-axial cables as repeater amplifiers or intermediate amplifiers to amplify low signals.
- TWTs have a long tube life, due to which they are used as power output tubes in communication satellites.
- Continuous wave high power TWTs are used in Troposcatter links, because of large power and large bandwidths, to scatter to large distances.
- TWTs are used in high power pulsed radars and ground based radars.

Magnetrons

Unlike the tubes discussed so far, Magnetrons are the cross-field tubes in which the electric and magnetic fields cross, i.e. run perpendicular to each other. In TWT, it was observed that electrons when made to interact with RF, for a longer time, than in Klystron, resulted in higher efficiency. The same technique is followed in Magnetrons.

Types of Magnetrons

There are three main types of Magnetrons.

Negative Resistance Type

- The negative resistance between two anode segments, is used.
- They have low efficiency.
- They are used at low frequencies (< 500 MHz).

Cyclotron Frequency Magnetrons

- The synchronism between the electric component and oscillating electrons is considered.
- Useful for frequencies higher than 100MHz.

Travelling Wave or Cavity Type

- The interaction between electrons and rotating EM field is taken into account.
- High peak power oscillations are provided.
- Useful in radar applications.

Cavity Magnetron

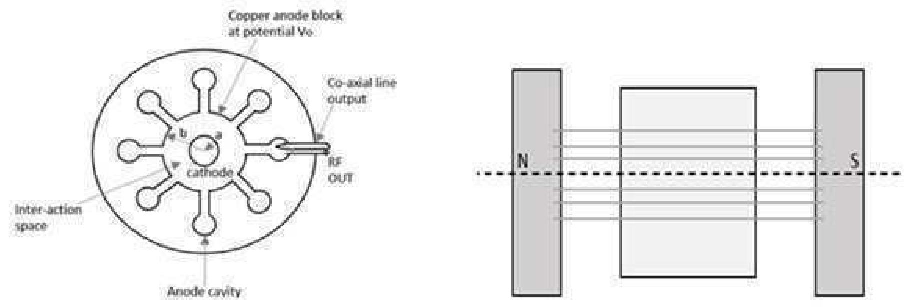
The Magnetron is called as Cavity Magnetron because the anode is made into resonant cavities and a permanent magnet is used to produce a strong magnetic field, where the action of both of these make the device work.

Construction of Cavity Magnetron

A thick cylindrical cathode is present at the center and a cylindrical block of copper, is fixed axially, which acts as an anode. This anode block is made of a number of slots that acts as resonant anode cavities.

The space present between the anode and cathode is called as Interaction space. The electric field is present radially while the magnetic field is present axially in the cavity magnetron. This magnetic field is produced by a permanent magnet, which is placed such that the magnetic lines are parallel to cathode and perpendicular to the electric field present between the anode and the cathode.

The following figures show the constructional details of a cavity magnetron and the magnetic lines of flux present, axially.



Construction details of a Cavity Magnetron   Magnetic flux lines in Magnetron (axial)

This Cavity Magnetron has 8 cavities tightly coupled to each other. An N-cavity magnetron has N modes of operations. These operations depend upon the frequency and the phase of oscillations. The total phase shift around the ring of this cavity resonators should be $2n\pi$ where n is an integer.

If ϕ_v represents the relative phase change of the AC electric field across adjacent cavities, then

$\phi_v=2\pi n/N$

Where $n=0,\pm1,\pm2,\pm(N/2-1),\pm N/2$

Which means that N/2 mode of resonance can exist if N is an even number.

If,

$n=N/2 \text{then} \phi_v=\pi$

This mode of resonance is called as $\pi-$mode.

$n=0 \text{then} \phi_v=0$

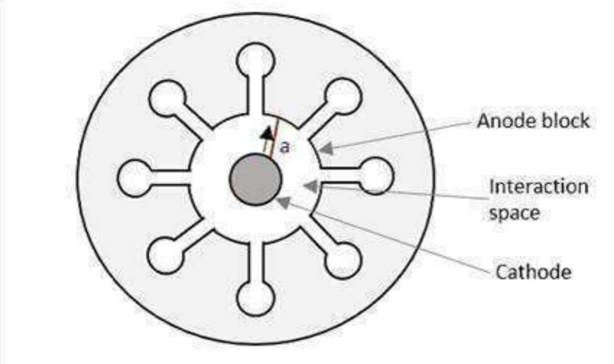
This is called as the Zero mode, because there will be no RF electric field between the anode and the cathode. This is also called as Fringing Field and this mode is not used in magnetrons.

Operation of Cavity Magnetron

When the Cavity Klystron is under operation, we have different cases to consider. Let us go through them in detail.

Case 1

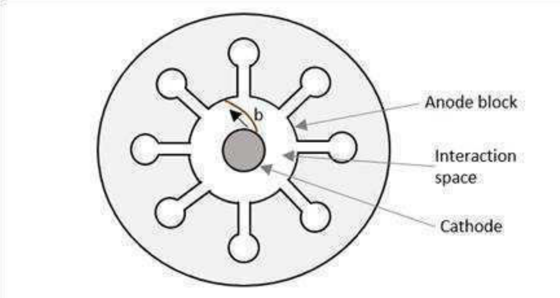
If the magnetic field is absent, i.e. B = 0, then the behavior of electrons can be observed in the following figure. Considering an example, where electron a directly goes to anode under radial electric force.



Movement of electron **a**, when no magnetic field is present

Case 2

If there is an increase in the magnetic field, a lateral force acts on the electrons. This can be observed in the following figure, considering electron b which takes a curved path, while both forces are acting on it.



Movement of electron **b** when small magnetic field is present

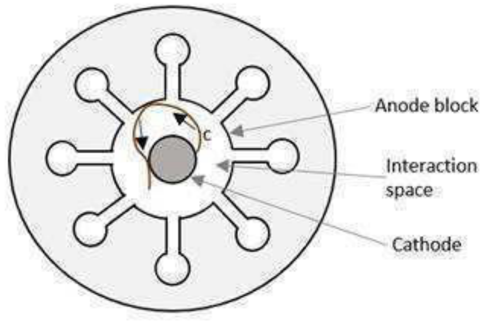
Radius of this path is calculated as

$R=mv/eB$

It varies proportionally with the velocity of the electron and it is inversely proportional to the magnetic field strength.

Case 3

If the magnetic field B is further increased, the electron follows a path such as the electron c, just grazing the anode surface and making the anode current zero. This is called as "Critical magnetic field" (B_c), which is the cut-off magnetic field. Refer the following figure for better understanding.



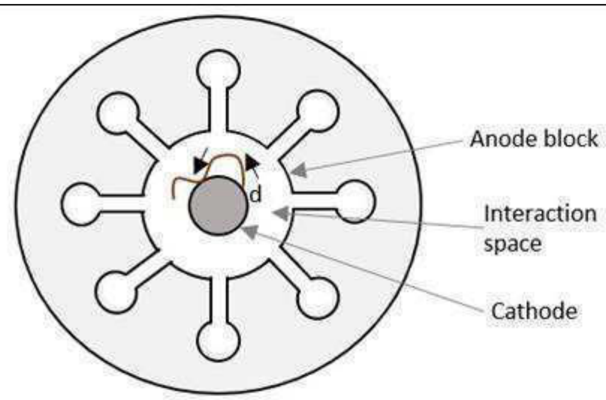
Movement of electron **c** when the magnetic field is critical magnetic field i.e. $B = B_c$

Case 4

If the magnetic field is made greater than the critical field,

$B > B_c$

Then the electrons follow a path as electron d, where the electron jumps back to the cathode, without going to the anode. This causes "back heating" of the cathode. Refer the following figure.



Movement of electron **d** when excessive magnetic field is present

This is achieved by cutting off the electric supply once the oscillation begins. If this is continued, the emitting efficiency of the cathode gets affected.

Operation of Cavity Magnetron with Active RF Field

We have discussed so far the operation of cavity magnetron where the RF field is absent in the cavities of the magnetron (static case). Let us now discuss its operation when we have an active RF field.

As in TWT, let us assume that initial RF oscillations are present, due to some noise transient. The oscillations are sustained by the operation of the device. There are three kinds of electrons emitted in this process, whose actions are understood as electrons a, b and c, in three different cases.

Case 1

When oscillations are present, an electron a, slows down transferring energy to oscillate. Such electrons that transfer their energy to the oscillations are called as favored electrons. These electrons are responsible for bunching effect.

Case 2

In this case, another electron, say b, takes energy from the oscillations and increases its velocity. As and when this is done,

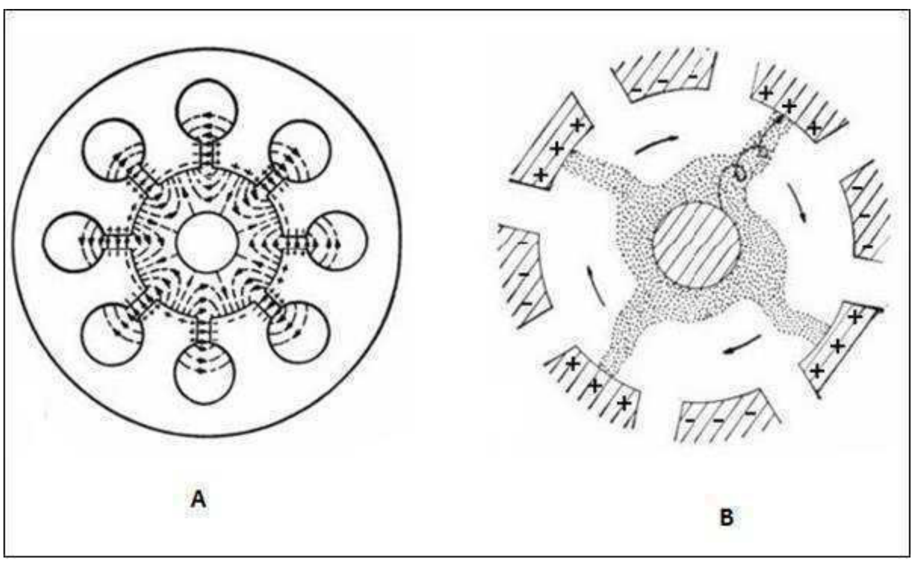
- It bends more sharply.
- It spends little time in interaction space.
- It returns to the cathode.

These electrons are called as unfavored electrons. They don't participate in the bunching effect. Also, these electrons are harmful as they cause "back heating".

Case 3

In this case, electron c, which is emitted a little later, moves faster. It tries to catch up with electron a. The next emitted electron d, tries to step with a. As a result, the favored electrons a, c and d form electron bunches or electron clouds. It called as "Phase focusing effect".

This whole process is understood better by taking a look at the following figure.



Phase Focusing Effect

Figure A shows the electron movements in different cases while figure B shows the electron clouds formed. These electron clouds occur while the device is in operation. The charges present on the internal surface of these anode segments, follow the oscillations in the cavities. This creates an electric field rotating clockwise, which can be actually seen while performing a practical experiment.

While the electric field is rotating, the magnetic flux lines are formed in parallel to the cathode, under whose combined effect, the electron bunches are formed with four spokes, directed in regular intervals, to the nearest positive anode segment, in spiral trajectories.