

Radartutorial

Book 5: “Velocity-modulated Tubes”

This educational endowment is a printable summary of all topics about “velocity modulates tubes” of the internet representation “Radar Basics” on www.radartutorial.eu , containing a lecture on the principles of radar technology.

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Learning Objectives:

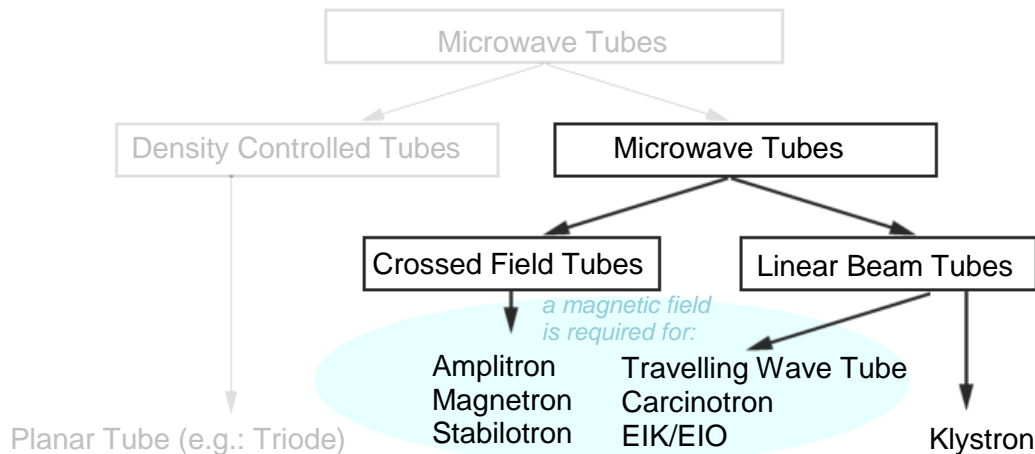
This chapter describes the different types of velocity modulated tubes used in radar sets. Upon completion of this chapter you will be able to:

- State the difference between velocity-modulated and density-controlled tubes;
- Associate microwave tubes to velocity-modulated or density-controlled tubes;
- Describe the principal construction and the mode of operation of
 - Klystron;
 - Travelling Wave Tube; and
 - Magnetron.

Velocity-modulated Tubes

Velocity-modulated tubes are microwave tubes using transit time in the conversion of dc power to radio-frequency power. The interchange of power is accomplished by using the principle of electron **velocity modulation** and low-loss resonant cavities in (or near the electron beam of) the microwave tube.

Velocity modulation is then defined as that variation in the velocity of a beam of electrons caused by the alternate speeding up and slowing down of the electrons in the beam. This variation is usually caused by a voltage signal applied between the grids through which the beam must pass. The direction of the electron beam and the static electrical field goes to each other parallelly (linearly) into linear beam tubes. Against this the fields influencing the electron beam stand vertically by the electron beam at the cross field tubes.



The following table compares with characteristic quantities of the velocity-modulated tubes used in radar technology. Although the planar tube isn't a velocity-modulated tube, it was included into this table for comparison purposes. The grid of the density controlled tube (like the planar triode) regulates the number of electrons on the path to the anode. The different speeds of the electrons by additional accelerating due the microwave voltage are annoying in this case. The cut-off frequency of density controlled tubes is relatively low. Higher frequencies need the use of velocity-modulated tubes, as shown in the table:

	Klystron	Traveling Wave Tube	Magnetron	Carcinotron	EIK/EIO	planar tube
<i>frequency</i>	up to 35 GHz	up to 95 GHz	up to 95 GHz	up to 5 GHz	up to 230 GHz	up to 1.5 GHz
<i>bandwidth</i>	2 - 4 %	10 - 20 %	any megahertzes	2 GHz	0.5...1%	30 - 50%
<i>power output</i>	up to 50 MW	up to 1 MW	up to 10 MW	1 W	up to 1 kW	up to 1 MW
<i>amplification</i>	up to 60 dB	up to 50 dB	–	–	40...50 dB	up to 20 dB
<i>function as</i>	small-band power amplifier	wide-band, lownoise voltage amplifier	high power oscillator at one frequency	frequency-controlled oscillator (VFO)	microwave amplifier/oscillator	amplifier, oscillator

Table 1: Comparing of velocity-modulated tubes

Klystron Amplifier

Klystron amplifiers are high power microwave vacuum tubes. They are used in some coherent radar transmitters as power amplifiers. Klystrons make use of the transit-time effect by varying the velocity of an electron beam. A klystron uses special resonant cavities which modulate the electric field around the axis of the tube modulating the electric field around the axis the tube. In the middle of these cavities, there is a grid allowing the electrons to pass the cavity.

Due to the number of the resonant cavities klystrons are divided up into

- Two- or Multicavity klystrons, and
- Reflex or Repeller Klystrons.

Two-Cavity Klystron

As the name implies, this klystron uses two cavities. The first cavity together with the first coupling device is called a “buncher”, while the second cavity with its coupling device is called a “catcher”.

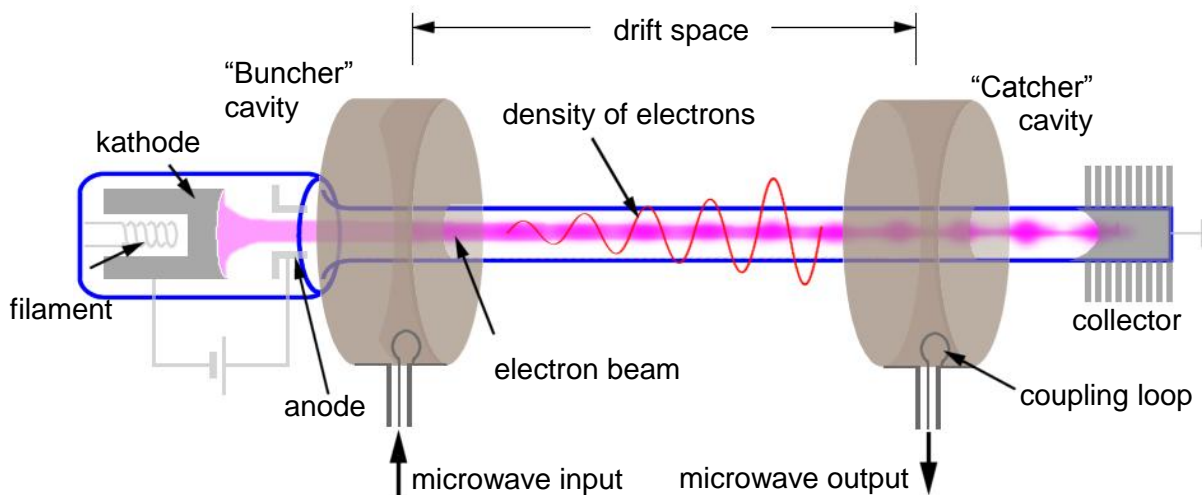


Figure 1: physical construction and mode of operation of a two-cavity klystron

The direction of the field changes with the frequency of the “buncher” cavity. These changes alternately accelerate and decelerate the electrons of the beam passing through the grids of the buncher cavity. The area beyond the cavities is called the “drift space”. The electrons form bunches in this area when the accelerated electrons overtake the decelerated electrons.

The function of the “catcher” cavity is to absorb energy from the electron beam. The “catcher” grids are placed along the beam at a point where the bunches are fully formed. The location is determined by the transit time of the bunches at the natural resonant frequency of the cavities (the resonant frequency of the catcher cavity is the same as the buncher cavity). The air-cooled collector collect the energy of the electron beam and change it into heat and X radiation.

Klystron amplification, power output, and efficiency can be greatly improved by the addition of intermediate cavities between the input and output cavities of the basic klystron. Additional cavities serve to velocity-modulate the electron beam and produce an increase in the energy available at the output.

Carcinotron¹

Carcinotron or backward wave oscillator (BWO), is a vacuum tube that is used to generate microwave oscillations. It belongs to the traveling-wave tube family, but the buncher and the catcher cavities are interchanged with each other. It is an oscillator with a wide electronic tuning range.

¹ Carcinotron is a trade name for backward wave tubes manufactured by CSF, now Thales

Reflex Klystron or Repeller Klystron

Another tube based on velocity modulation, and used to generate microwave energy, is the reflex klystron (repeller klystron). The reflex klystron contains a reflector plate, referred to as the repeller, instead of the output cavity used in other types of klystrons. The electron beam is modulated as it was in the other types of klystrons by passing it through an oscillating resonant cavity, but here the similarity ends.

The feedback required to maintain oscillations within the cavity is obtained by reversing the beam and sending it back through the cavity. The electrons in the beam are velocity-modulated before the beam passes through the cavity the second time and will give up the energy required to maintain oscillations. The electron beam is turned around by a negatively charged electrode that repels the beam (“repeller”). This type of klystron oscillator is called a reflex klystron because of the reflex action of the electron beam.

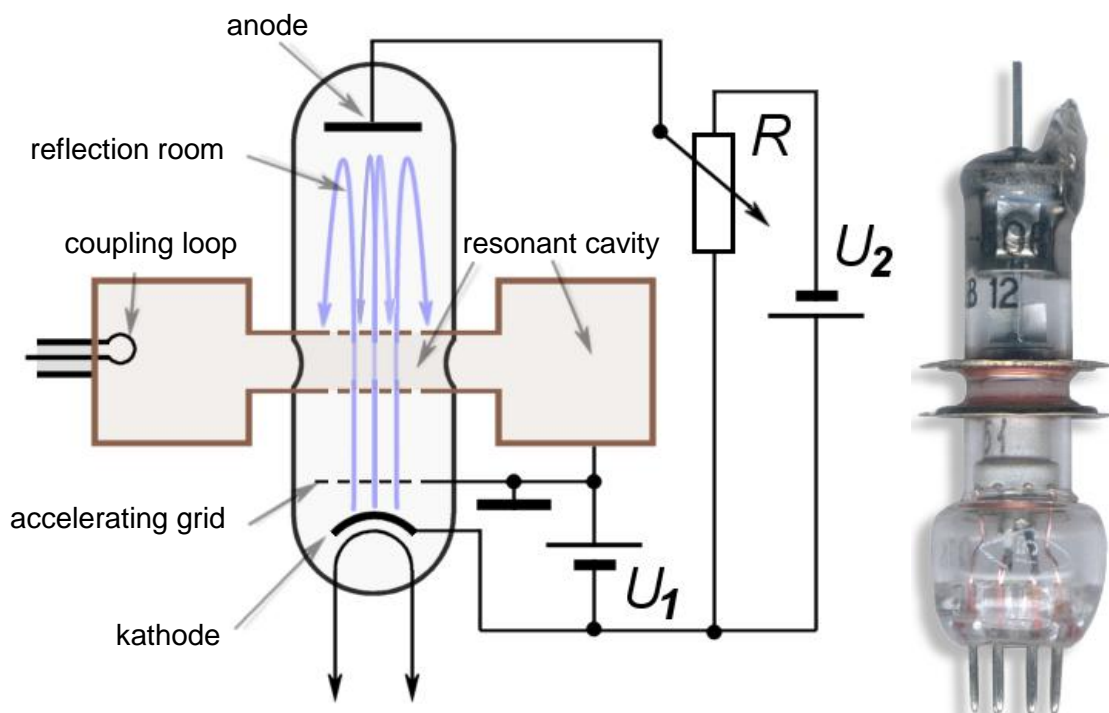


Figure 2: Wiring with a repeller klystron, and an example given low power repeller klystron tube

Repeller klystrons are often used in older radar sets as local oscillators or as oscillators in measurement sets. If the voltage feed is keyed, then the repeller klystron can be used for RF-pulse generation too, but as self-oscillating tube it provides a non-coherent oscillation only.

Traveling Wave Tube

Traveling wave tubes (TWT) are wideband amplifiers. They take therefore a special position under the velocity-modulated tubes. On reason of the special low-noise characteristic often they are in use as an active RF amplifier element in receivers additional. There are two different groups of TWT:

- low-power TWT for receivers occurs as a highly sensitive, low-noise and wideband amplifier in radar equipments
- high-power TWT for transmitters these are in use as a pre-amplifier or final stage for high-power transmitters.

Physical construction and functional describing

The Traveling Wave Tube (TWT) is a high-gain, low-noise, wide-bandwidth microwave amplifier. It is capable of gains greater than 40 dB with bandwidths exceeding an octave. (A bandwidth of one octave is one in which the upper frequency is twice the lower frequency.) Traveling-wave tubes have been designed for frequencies as low as 300 megahertz 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.

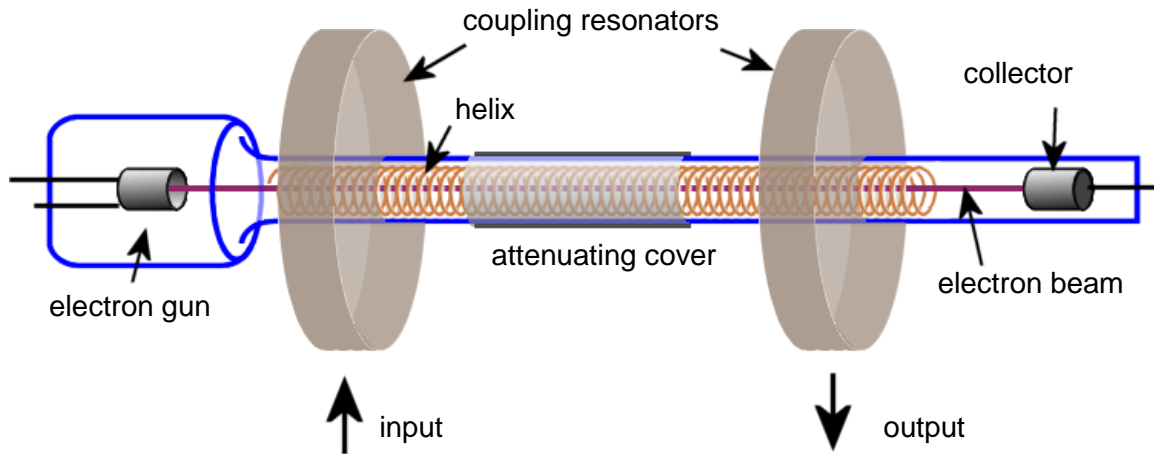


Figure 3. - Physical construction of a TWT

The physical construction of a typical TWT is shown in Figure 3. The TWT contains an electron gun which produces and then accelerates an 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 tight beam. The helix, at the center of the tube, is a coiled wire that provides a low-impedance transmission line for the RF energy within the tube. The RF input and output are coupled onto and removed from the helix by waveguide directional couplers that have no physical connection to the helix. The attenuator prevents any reflected waves from traveling back down the helix.

The following figure shows the electric fields that are parallel to the electron beam inside the helical conductor.

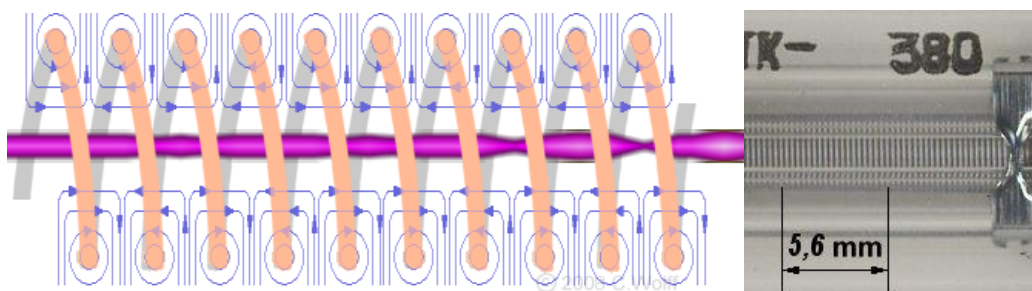


Figure 4. - electron- beam bunching and a detail-foto of a helix (Measure detail for 20 windings)

The electron- beam bunching already starts at the beginning of the helix and reaches its highest expression on the end of the helix. If the electrons of the beam were accelerated to travel faster than the waves traveling on the wire, bunching would occur through the effect of velocity modulation. Velocity modulation would be caused by the interaction between the traveling-wave fields and the electron beam. Bunching would cause the electrons to give up energy to the traveling wave if the fields were of the correct polarity to slow down the bunches. The energy from the bunches would increase the amplitude of the traveling wave in a progressive action that would take place all along the length of the TWT.

Characteristics of a TWT

The attainable **power-amplification** is essentially dependent on the following factors:

- constructive details (e.g. length of the helix)
- electron beam diameter (adjustable by the density of the focussing magnetic field)
- power input (see figure 5)
- voltage U_{A2} on the helix

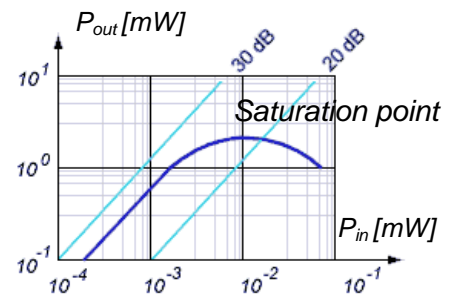


Figure 5: Characteristic of a traveling wave tube

As shown in the Figure 5, the gain of the TWT has got a linear characteristic of about 26 dB at small input power. If you increase the input power, the output power doesn't increase for the same gain. So you can prevent an oversteer of e.g the following mixer stage. The relatively low efficiency of the TWT partially offsets the advantages of high gain and wide bandwidth.

Given that the gain of an TWT effect by the electrons of the beam that interact with the electric fields on the delay structure, the frequency behaviour of the helix is responsible for the gain. The bandwidth of commonly used TWT can achieve values of many gigahertzes. The noise figure of recently used TWT is 3 ... 10 dB.

The helix may be replaced by some other slow wave structure such as a ring-bar, ring loop, or coupled cavity structure. The structure is chosen to give the characteristic appropriate to the desired gain/bandwidth and power characteristics.



Figure 6: Ring-Loop slow wave structure

Ring-Loop TWT

A Ring Loop TWT uses loops as slow wave structure to tie the rings together. These devices are capable of higher power levels than conventional helix TWTs, but have significantly less bandwidth of 5...15 percent and lower cut-off frequency of 18 GHz.

The feature of the ring-loop slow wave structure is high coupling impedance and low harmonic wave components. Therefore ring-loop traveling wave tube has advantages of high gain (40...60 Decibels), small dimension, higher operating voltage and less danger of the backward wave oscillation.

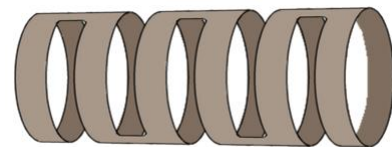


Figure 7: Ring-Bar slow wave structure

Ring-Bar TWT

The Ring-Bar TWT has got characteristics likely the Ring-Loop TWT. The slow wave structure can be made easier by cut-out the structure of a copper tube.

Coupled-cavity TWT

The Coupled-cavity TWT uses a slow wave structure of a series of cavities coupled to one another. The resonant cavities are coupled together with a transmission line. The electron beam (shown in Figure 8 as red beam) is velocity modulated by an RF input signal at the first resonant cavity. This RF energy (displayed as blue arrow) travels along the cavities and induces RF voltages in each subsequent cavity.

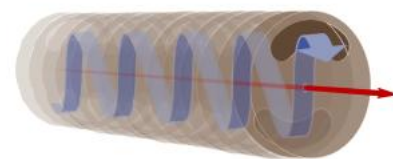


Figure 8: Coupled-cavity slow wave structure

If the spacing of the cavities is correctly adjusted, the voltages at each cavity induced by the modulated beam are in phase and travel along the transmission line to the output, with an additive effect, so that the output power is much greater than the power input.

Magnetron

In 1921 Albert Wallace Hull invented the magnetron as a microwave tube. During World War II it was developed by John Randall and Henry Boot to a powerful microwave generator for Radar applications.

Magnetrons function as self-excited microwave oscillators. Crossed electron and magnetic fields are used in the magnetron to produce the high-power output required in radar equipment. These multicavity devices may be used in radar transmitters as either pulsed or cw oscillators at frequencies ranging from approximately 600 to 96,000 megahertz. The relatively simple construction has the disadvantage, that the Magnetron usually can work only on a constructively fixed frequency.



Figure 9: Magnetron MI 29Г of the old Russian Radar "Bar Lock"

Physical construction of a magnetron

The magnetron is classed as a diode because it has no grid. The anode of a magnetron is fabricated into a cylindrical solid copper block. The cathode and filament are at the center of the tube and are supported by the filament leads. The filament leads are large and rigid enough to keep the cathode and filament structure fixed in position. The cathode is indirectly heated and is constructed of a high-emission material. The 8 up to 20 cylindrical holes around its circumference are resonant cavities. The cavities control the output frequency. A narrow slot runs from each cavity into the central portion of the tube dividing the inner structure into as many segments as there are cavities.

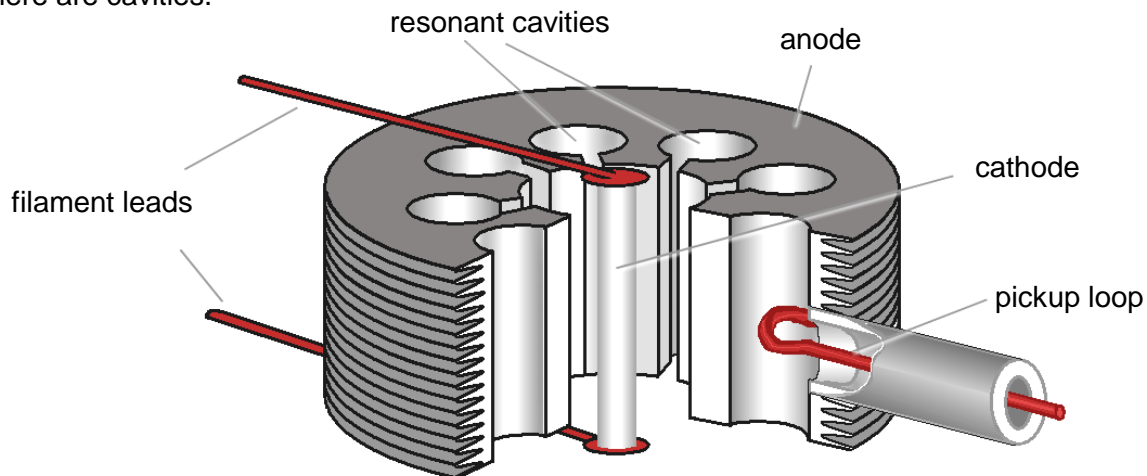


Figure 10: Cutaway view of a magnetron

The open space between the plate and the cathode is called the interaction space. In this space the electric and magnetic fields interact to exert force upon the electrons. The magnetic field is usually provided by a strong, permanent magnet mounted around the magnetron so that the magnetic field is parallel with the axis of the cathode.

The form of the cavities varies, as shown in Figure 11. The output lead is usually a probe or loop extending into one of the tuned cavities and coupled into a waveguide or coaxial line.

- a) slot- type
- b) vane- type
- c) rising sun- type
- d) hole-and-slot- type

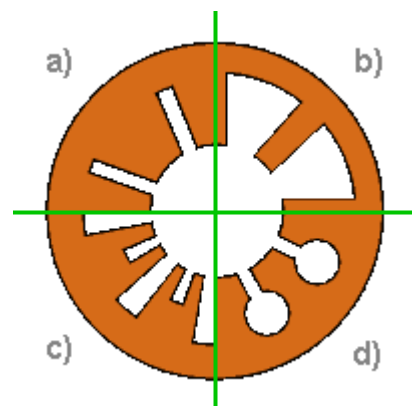


Figure 11: forms of the plate of magnetrons

Basic Magnetron Operation

As when all velocity-modulated tubes the electronic events at the production microwave frequencies at a Magnetron can be subdivided into four phases too:

1. phase: production and acceleration of an electron beam
2. phase: velocity-modulation of the electron beam
3. phase: bunching the electrons, forming of a „Space-Charge Wheel“
4. phase: dispense energy to the ac field

1. Phase: Production and acceleration of an electron beam

When no magnetic field exists, heating the cathode results in a uniform and direct movement of the field from the cathode to the plate (the blue path in Figure 12). The permanent magnetic field bends the electron path. If the electron flow reaches the plate, so a large amount of plate current is flowing. If the strength of the magnetic field is increased, the path of the electron will have a sharper bend. Likewise, if the velocity of the electron increases, the field around it increases and the path will bend more sharply. However, when the critical field value is reached, as shown in the figure as a red path, the electrons are deflected away from the plate and the plate current then drops quickly to a very small value. When the field strength is made still greater, the plate current drops to zero.

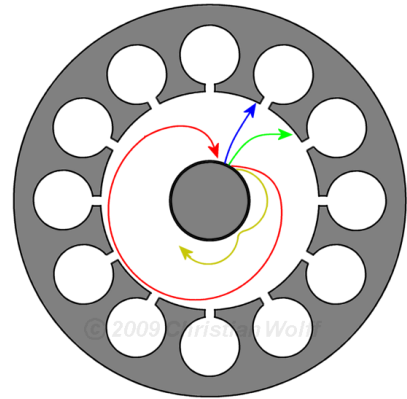


Figure 12: the electron path under the influence of different strength of the magnetic field

When the magnetron is adjusted to the cutoff, or critical value of the plate current, and the electrons just fail to reach the plate in their circular motion, it can produce oscillations at microwave frequencies.

2. Phase: Velocity-modulation of the electron beam

The electric field in the magnetron oscillator is a product of ac and dc fields. The dc field extends radially from adjacent anode segments to the cathode. The ac fields, extending between adjacent segments, are shown at an instant of maximum magnitude of one alternation of the rf oscillations occurring in the cavities.

In the Figure 13 is shown only the assumed high-frequency electrical ac field. This ac field work in addition to the to the permanently available dc field. The ac field of each individual cavity increases or decreases the dc field like shown in the figure.

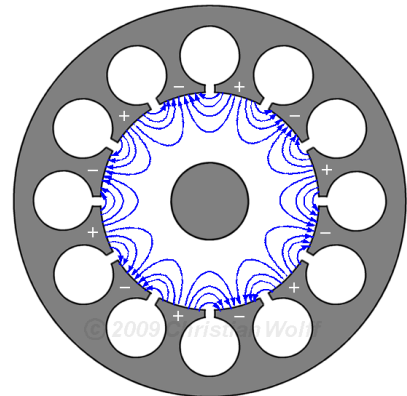


Figure 13: The high-frequency electrical field

Well, the electrons which fly toward the anode segments loaded at the moment more positively are accelerated in addition. These get a higher tangential speed. On the other hand the electrons which fly toward the segments loaded at the moment more negatively are slow down. These get consequently a smaller tangential speed.

3. Phase: Forming of a „Space-Charge Wheel”

On reason the different speeds of the electron groups a velocity modulation appears therefore.

The cumulative action of many electrons returning to the cathode while others are moving toward the anode forms a pattern resembling the moving spokes of a wheel known as a “Space-Charge Wheel”, as indicated in Figure 14. The space-charge wheel rotates about the cathode at an angular velocity of 2 poles (anode segments) per cycle of the ac field. This phase relationship enables the concentration of electrons to continuously deliver energy to sustain the rf oscillations.

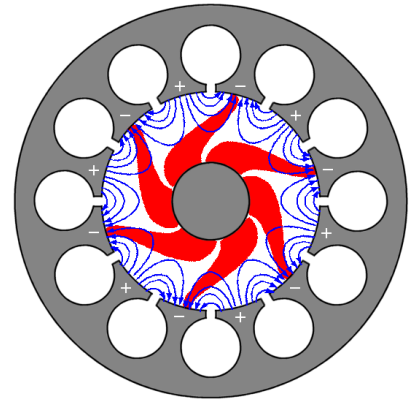


Figure 14: Rotating space-charge wheel in an twelve-cavity magnetron

One of the spokes just is near an anode segment which is loaded a little more negatively. The electrons are slowed down and pass her energy on to the ac field. This state isn't static, because both the ac- field and the wire wheel permanently circulate. The tangential speed of the electron spokes and the cycle speed of the wave must be brought in agreement so.

4. Phase: Dispense energy to the ac field

Recall that an electron moving against an E field is accelerated by the field and takes energy from the field. Also, an electron dispense energy to a field and slows down if it is moving in the same direction as the field (positive to negative). The electron spends energy to each cavity as it passes and eventually reaches the anode when its energy is expended. Thus, the electron has helped sustain oscillations because it has taken energy from the dc field and given it to the ac field. This electron describes the path shown in Figure 15 over a longer time period looked. By the multiple breaking of the electron the energy of the electron is used optimally. The effectiveness reaches values up to 80%.

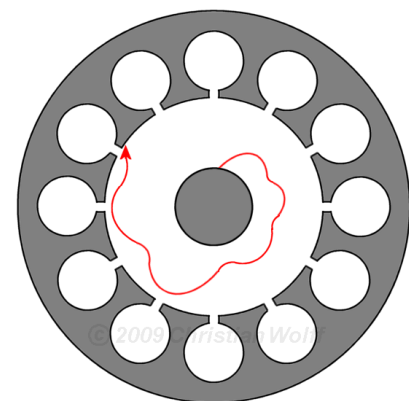


Figure 15: Path of a single electron under influence of the electric RF-field

Modes of Operation

The operation frequency depends on the sizes of the cavities and the interaction space between anode and cathode. But the single cavities are coupled over the interaction space with each other. Therefore several resonant frequencies exist for the complete system. Two of the four possible waveforms of a magnetron with 8 cavities are in the figure 8 represented. Several other modes of oscillation are possible ($3/4\pi$, $1/2 \pi$, $1/4 \pi$), but a magnetron operating in the π mode has greater power and output and is the most commonly used.

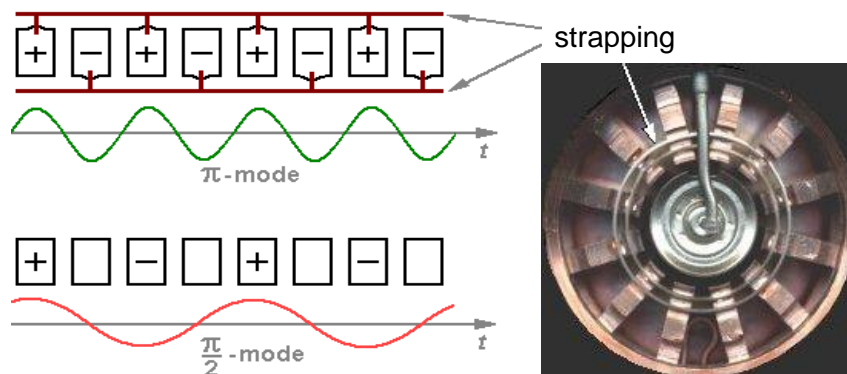


Figure 16: Waveforms of the magnetron (Anode segments are represented „unwound”) and a cutaway view of a magnetron (vane-type), showing the strapping rings and the slots.

So that a stable operational condition adapts in the optimal π mode, two constructive measures are possible:

- **Strapping rings:** The frequency of the π mode is separated from the frequency of the other modes by strapping to ensure that the alternate segments have identical polarities. For the π mode, all parts of each strapping ring are at the same potential; but the two rings have alternately opposing potentials. For other modes, however, a phase difference exists between the successive segments connected to a given strapping ring which causes current to flow in the straps.
- Use of cavities of **different resonance frequency**
E.g. such a variant is the anode form “Rising Sun” (see: Figure 11).

Magnetron coupling methods

Energy (RF) can be removed from a magnetron by means of a coupling loop. At frequencies lower than 10,000 megahertz, the coupling loop is made by bending the inner conductor of a coaxial line into a loop. The loop is then soldered to the end of the outer conductor so that it projects into the cavity, as shown in Figure 17, view (A). Locating the loop at the end of the cavity, as shown in view (B), causes the magnetron to obtain sufficient pickup at higher frequencies.

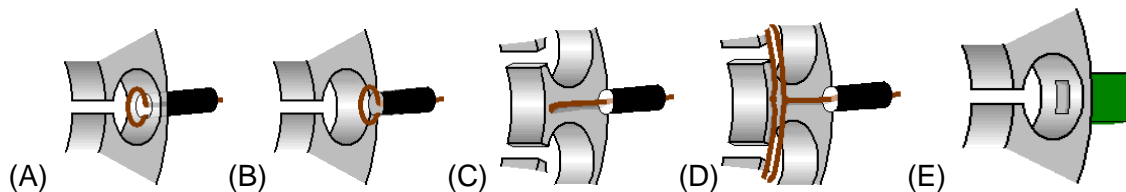


Figure 17: Magnetron coupling

The segment-fed loop method is shown in view (C) of Figure 17. The loop intercepts the magnetic lines passing between cavities. The strap-fed loop method (view (D)), intercepts the energy between the strap and the segment. On the output side, the coaxial line feeds another coaxial line directly or feeds a waveguide through a choke joint. The vacuum seal at the inner conductor helps to support the line. Aperture, or slot, coupling is illustrated in view (E). Energy is coupled directly to a waveguide through an iris.

Magnetron Tuning

A tunable magnetron permits the system to be operated at a precise frequency anywhere within a band of frequencies, as determined by magnetron characteristics. The resonant frequency of a magnetron may be changed by varying the inductance or capacitance of the resonant cavities.

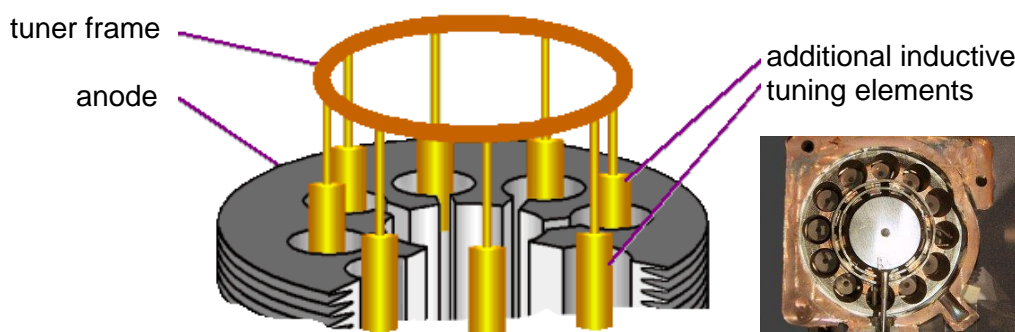


Figure 13: Resonant cavities of an hole-and-slot-type magnetron with inductive tuning elements

Examples given of tunable magnetrons is the M5114B used by the ATC- Radar ASR-910 and the TH3123 used in ATC-radar Thomson ER713S. To reduce mutual interferences, ATC-radars can work on different assigned frequencies. The frequency of the transmitter must be tunable therefore. This magnetron is provided with a mechanism to adjust the Tx- frequency exactly.

Crossed-Field Amplifier

Also other names are used for the **Crossed-Field Amplifier** in the literature.

- Platinotron
- Amplitron²
- Stabilotron

The Crossed-Field Amplifier (CFA), is a broadband microwave amplifier that can also be used as an oscillator (Stabilotron). The CFA is similar in operation to the magnetron and is capable of providing relatively large amounts of power with high efficiency. The bandwidth of the cfa, at any given instant, is approximately plus or minus 5 percent of the rated center frequency. Any incoming signals within this bandwidth are amplified. Peak power levels of many megawatts and average power levels of tens of kilowatts average are, with efficiency ratings in excess of 70 percent, possible with crossed-field amplifiers.

Because of the desirable characteristics of wide bandwidth, high efficiency, and the ability to handle large amounts of power, the CFA is used in many applications in microwave electronic systems. When used as the intermediate or final stage in high-power radar systems, all of the advantages of the CFA are used.

The amplifiers in this type of power-amplifier transmitter must be broad-band microwave amplifiers that amplify the input signals without frequency distortion. Typically, the first stage and the second stage are traveling-wave tubes (TWT) and the final stage is a crossed-field amplifier. Recent technological advances in the field of solid-state microwave amplifiers have produced solid-state amplifiers with enough output power to be used as the first stage in some systems. Transmitters with more than three stages usually use crossed-field amplifiers in the third and any additional stages. Both traveling-wave tubes and crossed-field amplifiers have a very flat amplification response over a relatively wide frequency range.

Crossed-field amplifiers have another advantage when used as the final stages of a transmitter; that is, the design of the crossed-field amplifier allows rf energy to pass through the tube virtually unaffected when the tube is not pulsed. When no pulse is present, the tube acts as a section of waveguide. Therefore, if less than maximum output power is desired, the final and preceding cross-field amplifier stages can be shut off as needed. This feature also allows a transmitter to operate at reduced power, even when the final crossed-field amplifier is defective.

Stabilotron is a crossed field amplifier using external resonant cavities as positive feed back loop. This is a kind of oscillating device like a magnetron, but, due to the higher accuracy of the external resonant cavities the stabilotron has got a more constant frequency.

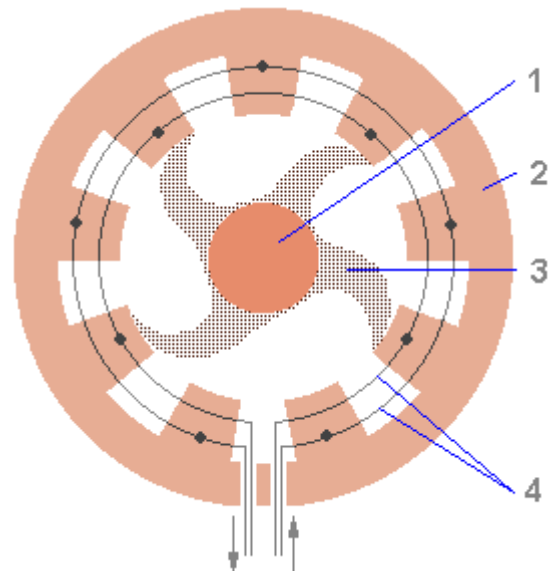


Figure 1: schematically view of a Crossed-Field Amplifier

- (1) kathode
- (2) anode with resonant-cavities
- (3) "Space-Charge Wheel"
- (4) delaying strapping rings

² "Amplitron" is a trademark of the Raytheon Manufacturing Company for the Raytheon line of crossed-field amplifiers.

Extended Interaction Klystron (EIK)

Extended Interaction Klystron (EIK) technology preserves the ruggedness and high power capability of the conventional Klystron. The EIK can be considered as a refinement of both two-cavity klystron and coupled-cavity TWT. The EIK is a velocity modulated tube as linear beam device which combines the advantages of both tubes, the ruggedness and high power capability of a klystron and the larger bandwidth of a TWT. It achieves enhanced power, bandwidth and efficiency at millimeter frequencies through the introduction of cavities with multiple coupled gaps. The number of cavities and interaction gaps can differ depending on required applications. A Ladder-type RF circuit supports high efficiency and thermal stability at millimeter and sub-millimeter frequencies, while operating with moderate electron beam voltages. The EIKs currently operate at frequencies from 18 to 280 GHz.

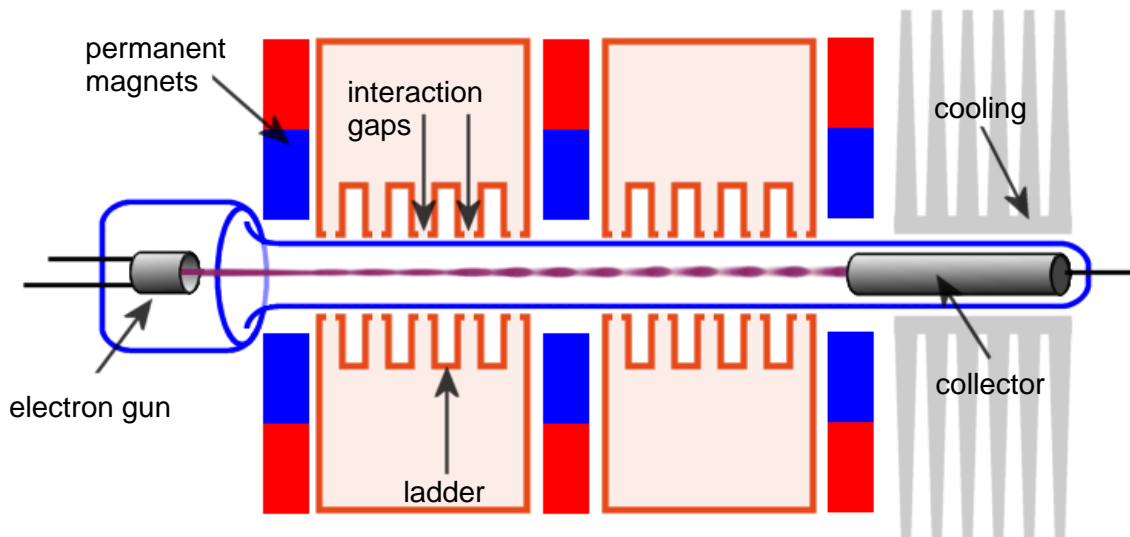


Figure 14: Principle of operation of an EIK

Figure 14 presents the principle of operation of an EIK; electrons are emitted from the cathode, a high convergence electron gun accelerates and focuses the cylindrical electron beam through an aperture in the anode. The electrons get a strong acceleration of the anode voltage and pass this electrode by a little hole in the anode. Beyond the anode, the linear beam, confined by the field of a permanent magnet, passes through a beam tunnel in the center of a series of cavities. Each cavity represents a short piece of the resonant slow-wave structure based on ladder geometry as like as the coupled cavities in a TWT. The number of SWS periods is selected to satisfy the conditions of RF stability and efficient beam modulation. The spent electron beam then leaves the circuit and is recovered in the depressed collector.

The multi-gap RF circuit has a simple, rugged geometry and is characterized by high impedance. This supports efficient modulation and energy exchange between the RF field and the electron beam over a broad instantaneous bandwidth.

High gain per length produces a short interaction circuit and provides the opportunity to use permanent magnets for focusing. The result is a well-focused electron beam in a relatively light package. In the case of pulsed operation, a focus electrode aperture grid is used to switch the beam. A short ladder length minimizes parasitic modes, and various methods for selective mode suppression ensure stable operation with low noise.

Extended Interaction Oscillator (EIO)

The Extended Interaction Oscillator (EIO) is a single cavity device with interaction gaps that function like a coupled-cavity TWT with extremely strong cavity-to-cavity coupling. At sufficient high beam currents, oscillations are sustained. Variation of the beam voltage allows up to 0.4% frequency tuning.