

# Magnetron

The magnetron is a high-powered vacuum tube that works as self-excited microwave oscillator. Crossed electron and magnetic fields are used in the magnetron to produce the high-power output required in radar equipment. These multi-cavity devices may be used in radar transmitters as either pulsed or CW oscillators at frequencies ranging from approximately 600 to 30,000 megahertz. The relatively simple construction has the disadvantage that the Magnetron usually can work only on a constructively fixed frequency.

## 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 directly heated and is constructed of a high-emission material. The 8 up to 20 cylindrical holes around its circumference are resonant cavities. 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. Each cavity works like a parallel resonant circuit. As depicted in figure 4 by the low frequency analogue, the rear wall of the structure of the anode bloc may be considered to as the inductive portion (a coil with a single turn). The vane tip region may be considered as the capacitor portion of the equivalent parallel resonant circuit. The resonant frequency of a microwave cavity is thereby determined by the physical dimension of the resonator. If a single resonant cavity oscillates, then it excites the next one to oscillate too. This one oscillates at a phase delay of 180 degrees and excites the next resonant cavity, and so on. From a resonant cavity to the next always occurs this delay of 180 degrees. The chain of resonators thus forms a slow-wave structure that is self-contained. Because of this slow-wave structure, this design is also called "*Multi-cavity Travelling Wave Magnetron*" in some publications.



Figure 1: Magnetron MI 29G (MI 29Г) of the old Russian radar "Bar Lock"

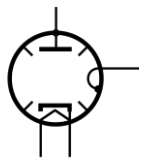


Figure 2: Symbol in electric circuits

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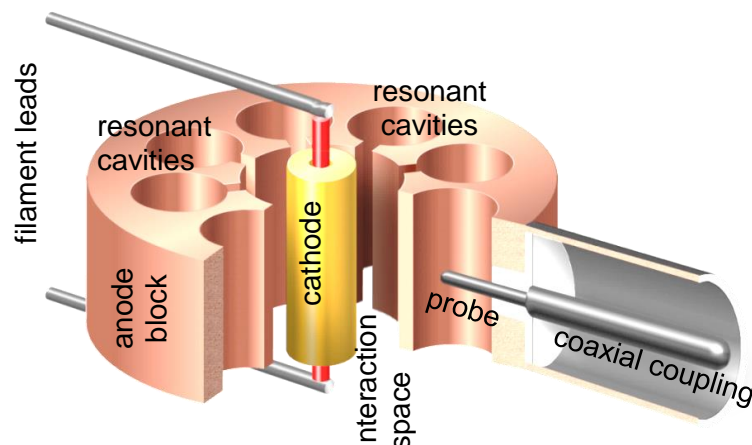


Figure 3: Cutaway view of a magnetron

The cathode of a magnetron provides the electrons through which the mechanism of energy transfer is accomplished. The cathode is located in the center of the anode and is made up of a hollow cylinder of emissive material (mostly Barium Oxide) surrounding a heater. The feeding wires of the filament must center the whole cathode. Any eccentricity between anode and cathode can cause serious internal arcing or malfunction.

The open space between the anode bloc 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.

It generally consists of an even number of microwave cavities arranged in radial fashion. The form of the cavities varies, as shown in the Figure 5:

- a. slot- type
- b. vane- type
- c. *Rising Sun*- type
- d. hole-and-slot- type

The slot type, hole-and slot type and the rising sun type are usually machined by hobbing methods out of solid copper stock. But it can be difficult to cut soft metal (such as copper) in a lathe. The vane type is generally made up of individual vanes assembled and brazed into a support ring therefore. The resonance behavior can be already tested and calibrated in the laboratory before the anode is installed in the vacuum tube. The output lead is usually a probe or a loop extending into one of the resonant cavities and coupled into a wave-guide or coaxial line.

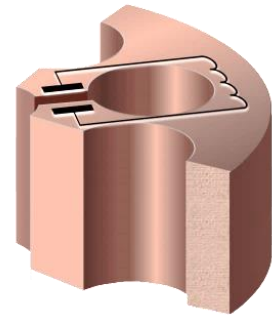


Figure 4: A resonant cavity in the anode block has the function of a parallel resonant circuit: The opposite anode walls of a slot are the capacitor, the detour around the hole is the inductance (with only one turn).

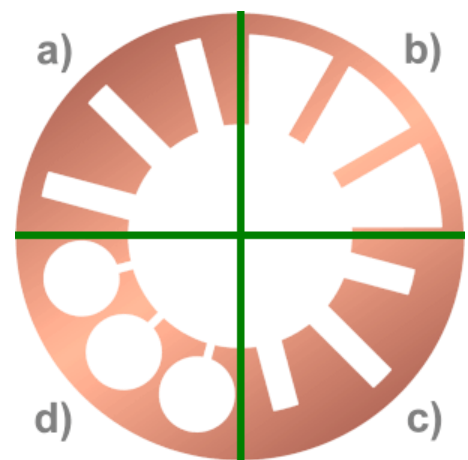


Figure 5: Different forms of the anode block in a magnetron

## Magnetron Basic Operation

As with all velocity-modulated tubes the generation of microwave frequencies in a magnetron can be subdivided into four phases:

1. Phase: Generation and acceleration of an electron beam in a dc field
2. Phase: Velocity-modulation of the electron beam in an ac field
3. Phase: Formation of electron bunches by velocity modulation (here in form of a "Space-Charge Wheel")
4. Phase: Dispensing of energy to the ac field

## 1. Phase: Generation and acceleration of an electron beam in a dc field

Since the cathode is kept at negative voltage, the static electric field is in radial direction from (grounded) anode block to the cathode. When no magnetic field exists, heating the cathode results in a uniform and direct movement of the electron from the cathode to the anode block (the blue path in Figure 6). A weak permanent magnetic field  $B$  perpendicular to the electric field bends the electron path as shown with the green path in Figure 6. If the electron flow reaches the anode, 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 Figure 6 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.

These values of the anode voltage and magnetic field strength that prevent an anode current are called *Hull* cut-off magnetic field and cut-off voltage. When the magnetron is adjusted to the cut-off, 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.

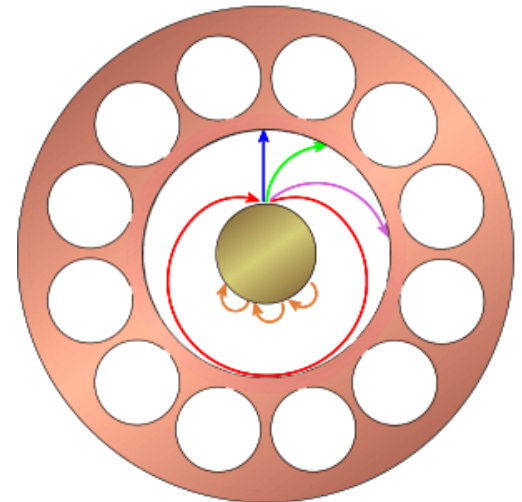


Figure 6: Trajectory of an electron under the influence of the electrostatic and the magnetic field for different magnetic flux densities.

## 2. Phase: Velocity-modulation of the electron beam

The electric field in the magnetron oscillator is a summary 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 6 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 Figure 7.

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.

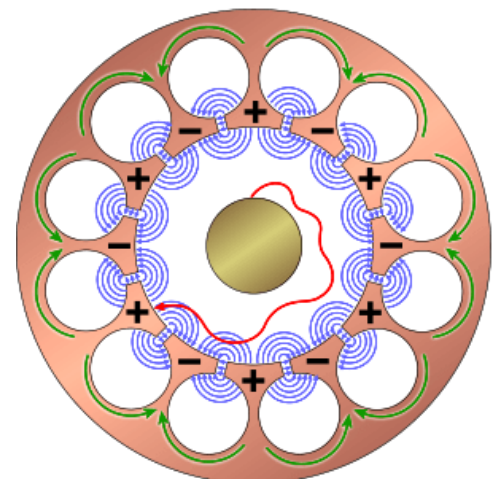


Figure 7: The influence of the high-frequency electrical field of the trajectory of an electron

### 3. Formation of electron bunches by velocity modulation

On reason the different speeds of the electron groups the velocity modulation leads to a density modulation 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 shown in Figure 8. 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.

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.

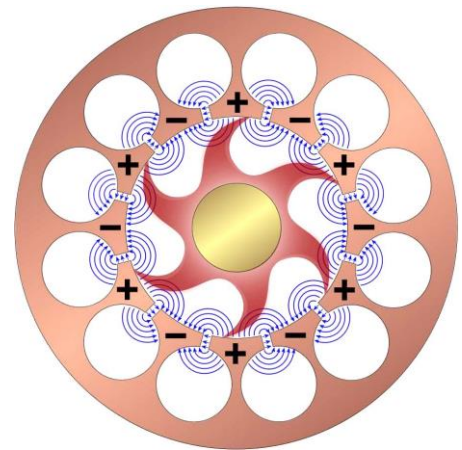


Figure 8: Rotating space-charge wheel in a twelve-cavity magnetron

### 4. Phase: Dispensing of 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 dispenses 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 5 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 percent.

#### **Transient oscillation**

After switching the anode voltage, there is still no RF field. The single electron moves under the influence of the static electric field of the anode voltage and the effect of the magnetic field as shown in Figure 6 by the red electron path. Electrons are charge carriers: during the flyby at a gap, they give off a small part of energy to the cavities. (Similar to a flute: A flute produces sound when a stream of air is flowing past an edge of a hole.) The cavity resonator begins to oscillate at its natural resonant frequency. Immediately begins the interaction between this RF field (with an initial low power) and the electron beam. The electrons are additionally influenced by the alternating field. It begins the process described in sequence of phase 1 to 4 of the interaction between RF field and the now velocity-modulated electrons.

Unfortunately, the transient oscillation doesn't begin with a predictable phase. Each transient oscillation occurs with a random phase. The transmitting pulses that are generated by a magnetron are therefore not coherent.

However, it is possible to get phase coherence, if the magnetron is fed with a continuous priming signal from a coherent oscillator.



## Modes of Oscillation

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 12 cavities are in the figure 9 represented. Several other modes of oscillation are possible ( $\frac{3}{4}\pi$  mode,  $\frac{1}{2}\pi$  mode,  $\frac{1}{4}\pi$  mode), but a magnetron operating in the  $\pi$  mode has a higher output power and is most commonly used. When operating the magnetron in one of the other modes ( $\frac{3}{4}\pi$ ,  $\frac{1}{2}\pi$ ,  $\frac{1}{4}\pi$ ) the power or the efficiency and the oscillation frequency decrease.

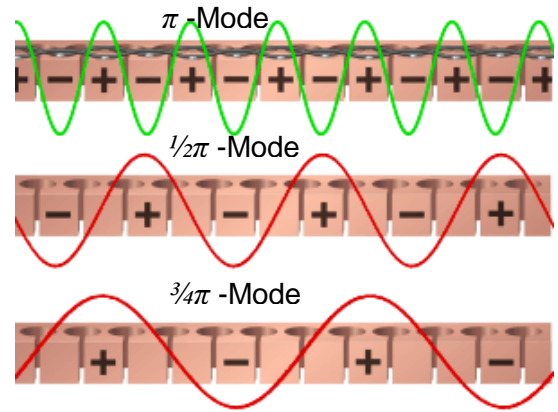


Figure 9: Modes of the magnetron (Anode segments are represented "unwound")

To ensure that a stable operational condition can be set in the optimal  $\pi$  mode, two constructive measures are possible:

1. **Strapping rings:**

The frequency of the  $\pi$  mode is separated from the frequency of the other modes by strapping to ensure that the alternate segments have identical polarities. For the  $\pi$  mode, all parts of each strapping ring are at the same potential; but the two rings have alternately opposing potentials. For other modes, a phase difference exists between the successive segments connected to a given strapping ring which causes current to flow in the straps.

2. Use of cavities of **different resonance frequency:** e.g. the anode form *Rising Sun*.

## Magnetron coupling methods

Energy (rf) can be removed from a magnetron by means of a coupling loop as shown in Figure 19 into the bottom one resonator. 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 11 also. Locating the loop at the end of the cavity, as shown in Figure 12, causes the magnetron to obtain sufficient pickup at higher frequencies.

The segment-fed loop method is shown in Figure 13. The loop intercepts the magnetic lines passing between cavities. The strap-fed loop method Figure 14, intercepts the energy between the strap and the segment. On the output side, the coaxial line feeds another coaxial line directly or feeds a wave-guide through a choke joint. The vacuum seal at the inner conductor helps to support the line. Aperture, or slot, coupling is illustrated in Figure 15. Energy is coupled directly to a wave-guide through an iris (made from either glass or ceramic).

Various methods of coupling the energy from the magnetron:

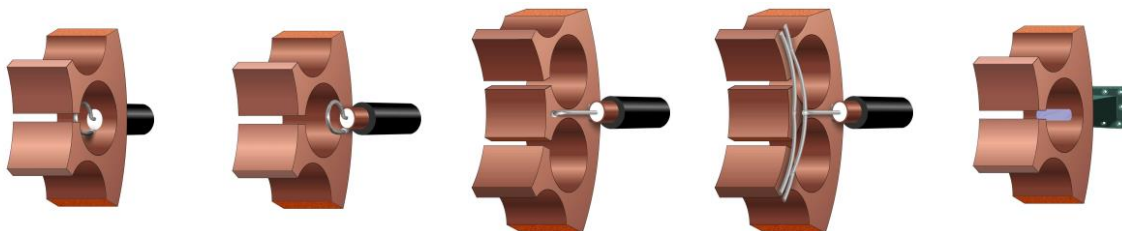


Figure 11: coupling loop into a resonator

Figure 12: coupling loop at the end of the resonator

Figure 13: segment-fed loop

Figure 14: strap-fed loop

Figure 15: Aperture coupling (or slot coupling)

## Magnetron tuning

An example of a tunable magnetron is the M5114B used by the ATC- Radar ASR-910. To reduce mutual interferences, the ASR-910 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 of the ASR-910 exactly.

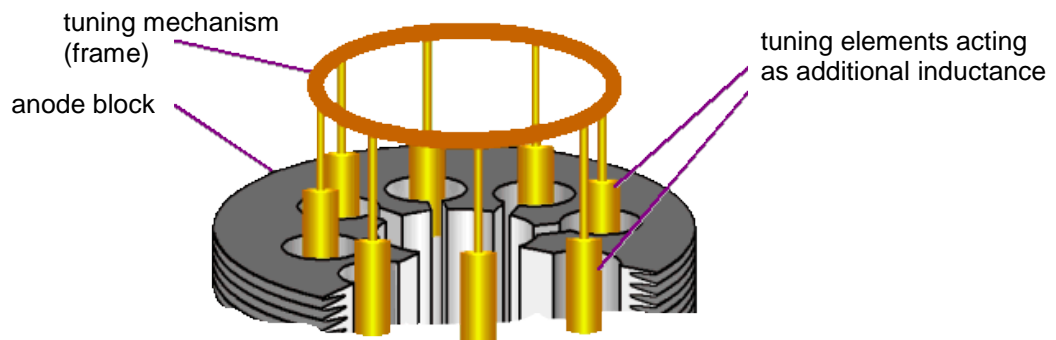


Figure 16: Inductive magnetron tuning ("Crown-of-thorns tuning")

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Figure 16 shows the inductive tuning elements of the TH3123 Magnetron used in ATC-radar Thomson ER713S. Note that the adjacent the filament supply lines resonant cavity and the coupling loop cavity are not tunable!



Figure 17: Magnetron M5114B of the ATC-radar ASR-910



Figure 18: Magnetron VMX1090 of the ATC-radar PAR-80. This magnetron is even equipped with the permanent magnets necessary for the work.

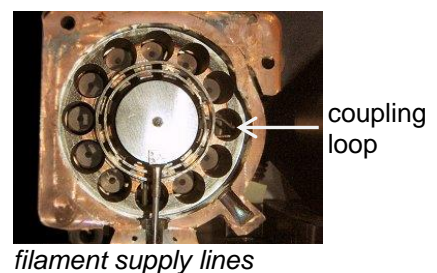


Figure 19: resonant cavities of a hole-and-slot-type magnetron with inductive tuning elements