The Traveling-Wave Tube

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 1 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. The physical construction of a typical TWT is shown in figure 2-13. 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 directional couplers that have no physical connection to the helix. If the RF energy is transported on coaxial cables, the coaxial couplers are wound in a helical manner similar to that shown in figure 2-13. If the RF energy is transported in waveguides, waveguide directional couplers are used. The attenuator prevents any reflected waves from traveling back down the helix.

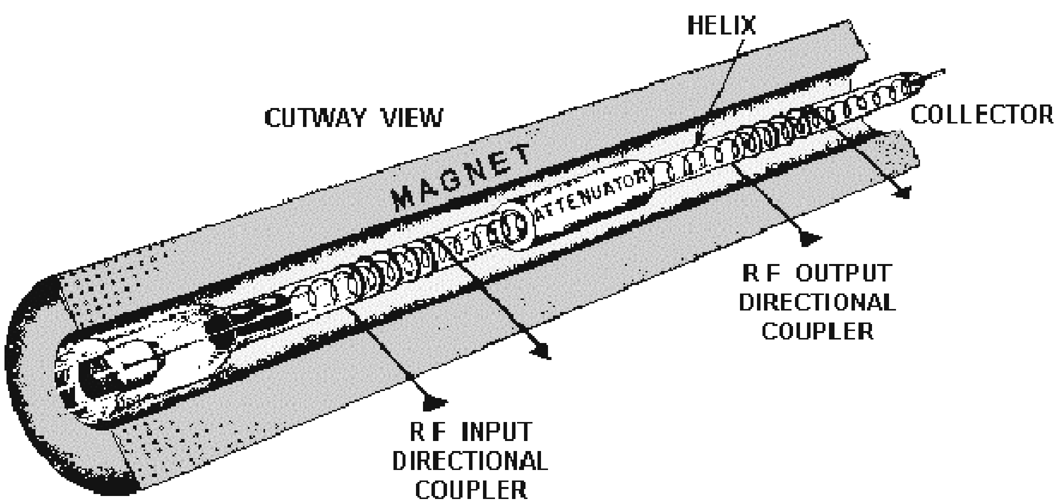

Figure 1.—Physical construction of a TWT.

A simplified version of TWT operation is shown in figure 2-14. In the figure, an electron beam is passing along a non-resonant transmission line represented by a straight wire. The input to the transmission line is an RF wave which travels on the line from input to output. The line will transport a wide range of RF frequencies if it is terminated in the characteristic impedance of the line. The electromagnetic waves traveling down the line produce electric fields that interact with the electrons of the beam.

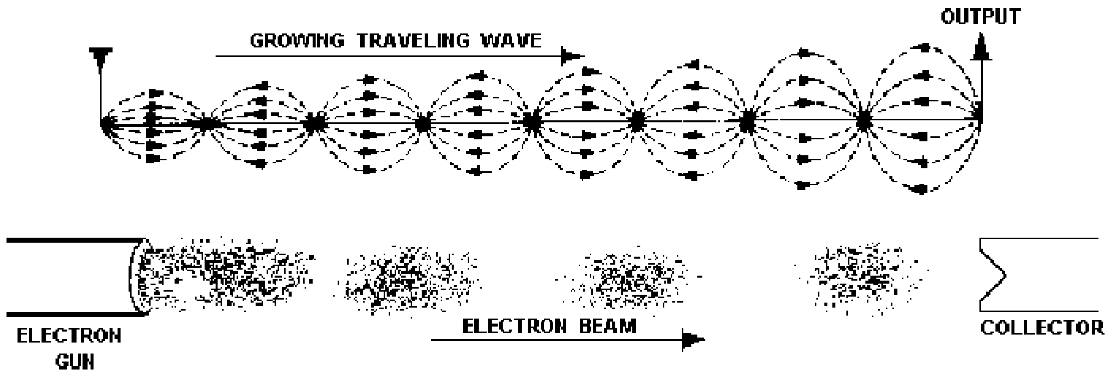

Figure 2—Simplified TWT.

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 bunch. 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, as shown in figure 2-14.

However, because the waves travel along the wire at the speed of light, the simple TWT shown in figure 2-14 will not work. At present no way is known to accelerate an electron beam to the speed of light. Since the electron beam cannot travel faster than the wave on the wire, bunching will not take place and the tube will not work. The TWT is therefore designed with a delay structure to slow the traveling wave down to or below the speed of the electrons in the beam. A common TWT delay structure is a wire, wound in the form of a long coil or helix, as shown in figure 2-15, view (A). The shape of the helix slows the effective velocity of the wave along the common axis of the helix and the tube to about one-tenth the speed of light. The wave still travels down the helix wire at the speed of light, but the coiled shape causes the wave to travel a much greater total distance than the electron beam. The speed at which the wave travels down the tube can be varied by changing the number of turns or the diameter of the turns in the helix wire. The helical delay structure works well because it has the added advantage of causing a large proportion of electric fields that are parallel to the electron beam. The parallel fields provide maximum interaction between the fields and the electron beam.

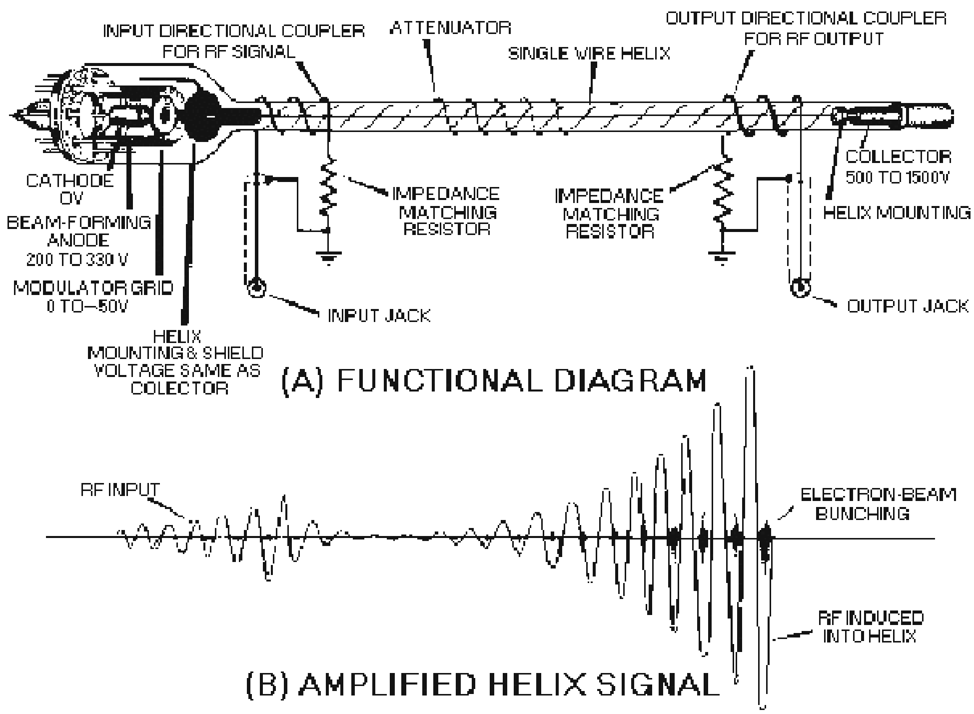

Figure 3—Functional diagram of a TWT.

In a typical TWT, the electron beam is directed down the center of the helix while, at the same time, an RF signal is coupled onto the helix. The electrons of the beam are velocity-modulated by the electric fields produced by the RF signal.

Amplification begins as the electron bunches form and release energy to the signal on the helix. The slightly amplified signal causes a denser electron bunch which, in turn, amplifies the signal even more. The amplification process is continuous as the RF wave and the electron beam travel down the length of the tube. Any portion of the TWT output signal that reflects back to the input will cause oscillations within the tube which results in a decrease in amplification. Attenuators are placed along the length of the helix to prevent reflections from reaching the input. The attenuator causes a loss in amplitude, as can be seen in figure 2-15, view (B), but it can be placed so as to minimize losses while still isolating the input from the output.

The relatively low efficiency of the TWT partially offsets the advantages of high gain and wide bandwidth. The internal attenuator reduces the gain of the tube, and the power required to energize the focusing magnet is an operational loss that cannot be recovered. The TWT also produces heat which must be dissipated by either air-conditioning or liquid-cooling systems. All of these factors reduce the overall efficiency of the TWT, but the advantages of high gain and wide bandwidth are usually enough to overcome the disadvantages.

The Magnetron

The MAGNETRON, shown in figure 2-17A, is a self-contained microwave oscillator that operates differently from the linear-beam tubes, such as the TWT and the klystron. Figure 2-17B is a simplified drawing of the magnetron. CROSSED-ELECTRON and MAGNETIC fields are used in the magnetron to produce the high-power output required in radar and communications equipment.

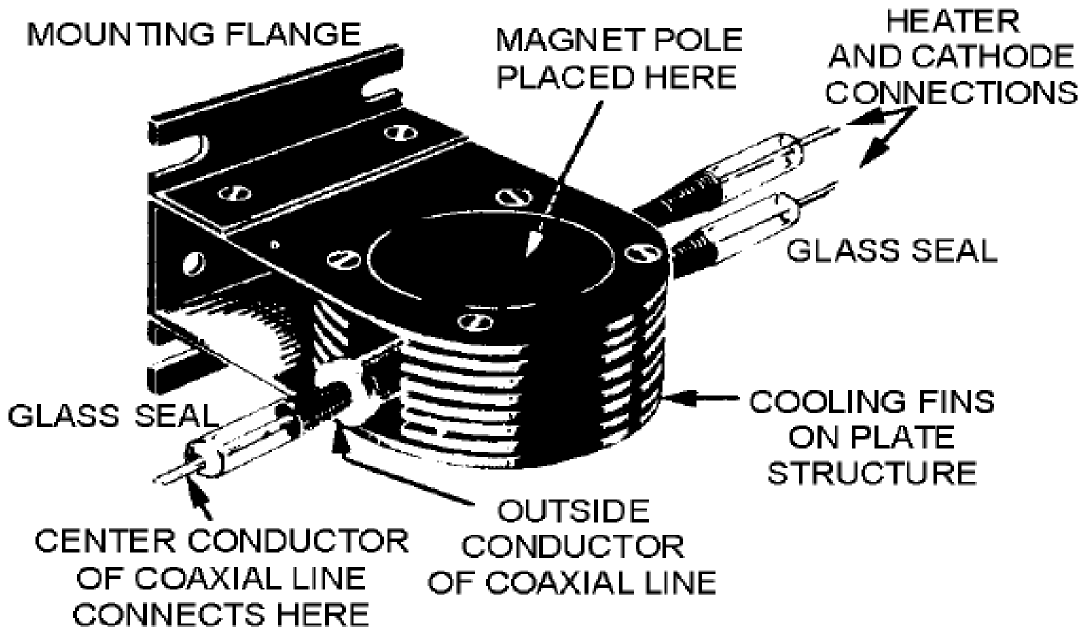

Figure 1—Magnetron.

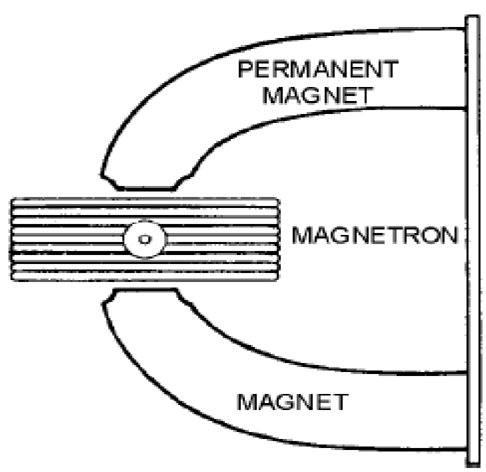

Figure 2—Magnetron.

The magnetron is classed as a diode because it has no grid. A magnetic field located in the space between the plate (anode) and the cathode serves as a grid. The plate of a magnetron does not have the same physical appearance as the plate of an ordinary electron tube. Since conventional inductive capacitive (LC) networks become impractical at microwave frequencies, the plate is fabricated into a cylindrical copper block containing resonant cavities which serve as tuned circuits. The magnetron base differs considerably from the conventional tube base. The magnetron base is short in length and has large diameter leads that are carefully sealed into the tube and shielded.

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 output's lead usually a probe or loop extending into one of the tuned cavities and coupled into a waveguide or coaxial line. The plate structure, shown in figure 2-18, is a solid block of copper. The 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. Alternate segments are strapped together to put the cavities in parallel with regard to the output. The cavities control the output frequency. The straps are circular, metal bands that are placed across the top of the block at the entrance slots to the cavities. Since the cathode must operate at high power, it must be fairly large and must also be able to withstand high operating temperatures. It must also have good emission characteristics, particularly under return bombardment by the electrons. This is because most of the output power is provided by the large number of electrons that are emitted when high-velocity electrons return to strike the cathode. The cathode is indirectly heated and is constructed of a high emission material. 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.

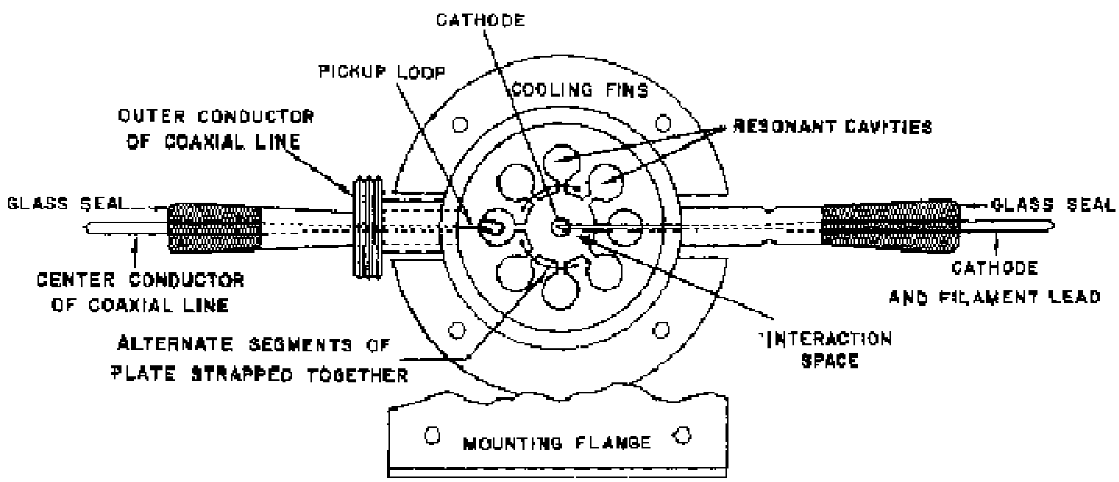

Figure 3—Cutaway view of a magnetron.

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 cathode is mounted in the center of the interaction space.

BASIC MAGNETRON OPERATION.—Magnetron theory of operation is based on the motion of electrons under the influence of combined electric and magnetic fields. The following information presents the laws governing this motion. The direction of an electric field is from the positive electrode to the negative electrode. The law governing the motion of an electron in an electric field (E field) states: The force exerted by an electric field on an electron is proportional to the strength of the field. Electrons tend to move from a point of negative potential toward a positive potential. This is shown in figure 2-19. In other words, electrons tend to move against the E field. When an electron is being accelerated by an E field, as shown in figure 2-19, energy is taken from the field by the electron.

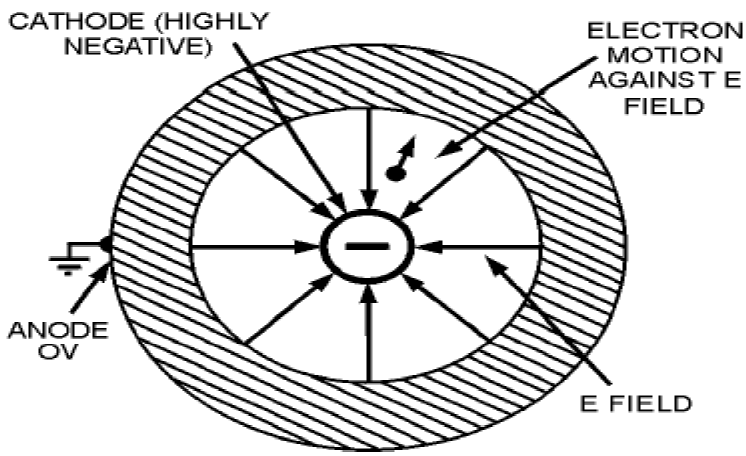

Figure 4—Electron motion in an electric field.

The law of motion of an electron in a magnetic field (H field) states:
The force exerted on an electron in a magnetic field is at right angles to both the field and the path of the electron. The direction of the force is such that the electron trajectories are clockwise when viewed in the direction of the magnetic field.
This is shown in figure 5.

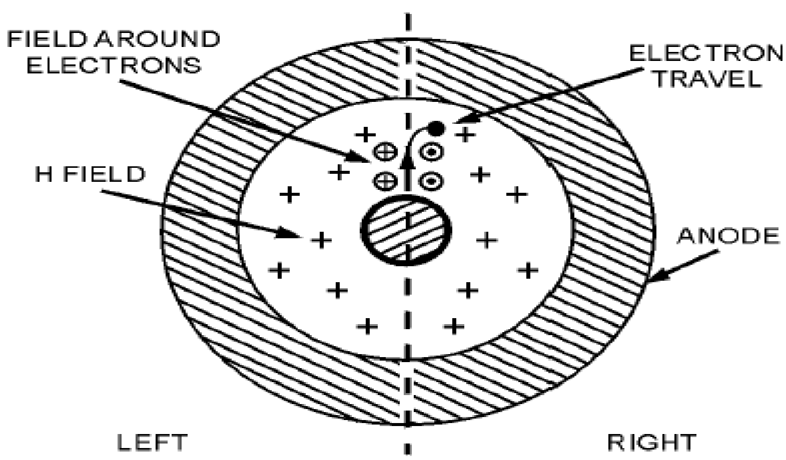

Figure 5.—Electron motion in a magnetic field.

In figure 2-20, assume that a south pole is below the figure and a north pole is above the figure so that the magnetic field is going into the paper. When an electron is moving through space, a magnetic field builds around the electron just as it would around a wire when electrons are flowing through a wire. In figure 2-20 the magnetic field around the moving electron adds to the permanent magnetic field on the left side of the electron's path and subtracts from the permanent magnetic field on the right side. This action weakens the field on the right side; therefore, the electron path bends to the right (clockwise). 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. A schematic diagram of a basic magnetron is shown in figure 2-21A. The tube consists of a cylindrical plate with a cathode placed along the center axis of the plate. The tuned circuit is made up of cavities in which oscillations take place and are physically located in the plate. When no magnetic field exists, heating the cathode results in a uniform and direct movement of the field from the cathode to the plate, as illustrated in figure 2-21B. However, as the magnetic field surrounding the tube is increased, a single electron is affected, as shown in figure 2-22. In figure 2-22, view (A), the magnetic field has been increased to a point where the electron proceeds to the plate in a curve rather than a direct path.

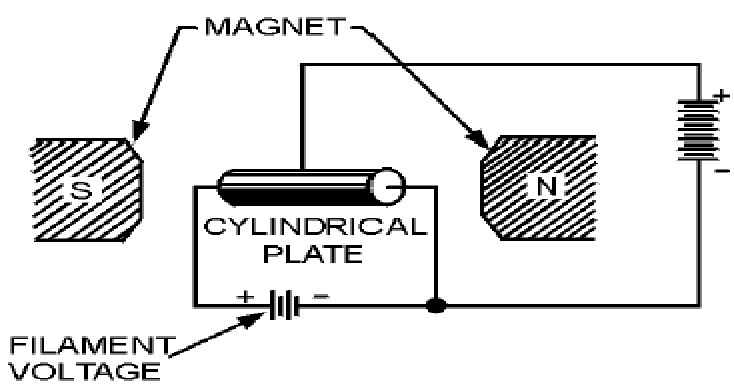

Figure 2-21A.—Basic magnetron. SIDE VIEW.

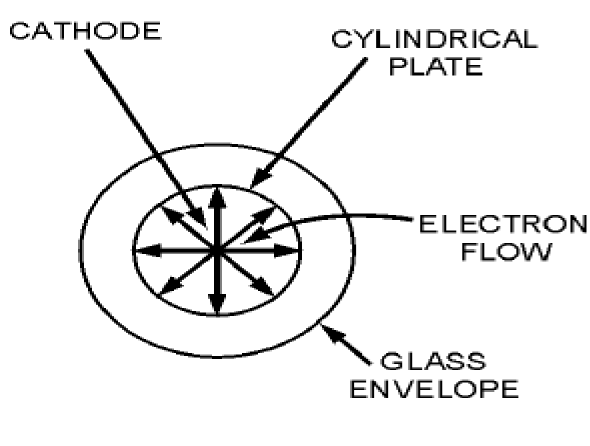

Figure 2-21B.—Basic magnetron. END VIEW OMITTING MAGNETS.

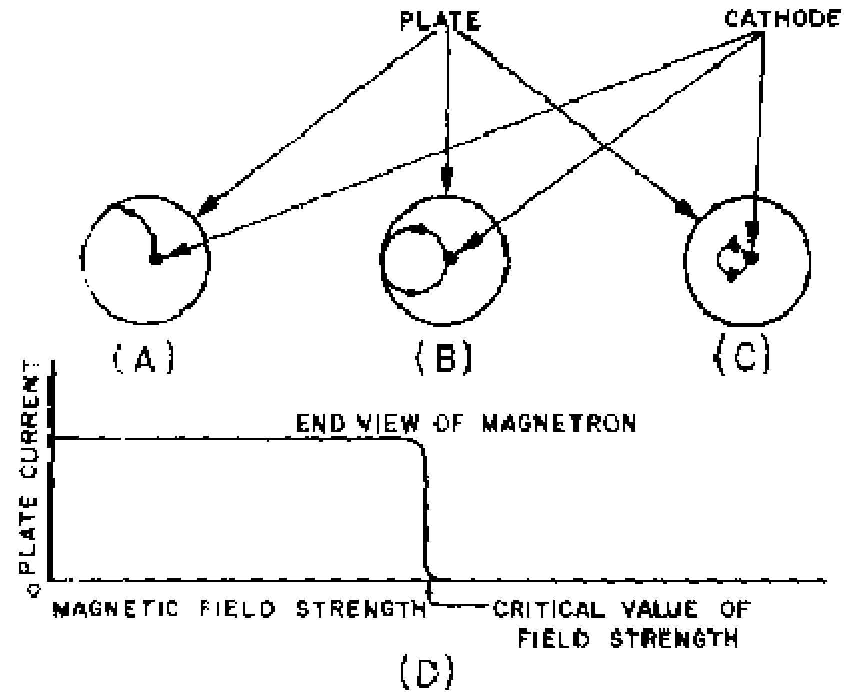

Figure 2-22.—Effect of a magnetic field on a single electron.

In view (B) of figure 2-22, the magnetic field has reached a value great enough to cause the electron to just miss the plate and return to the filament in a circular orbit. This value is the CRITICAL VALUE of field strength. In view (C), the value of the field strength has been increased to a point beyond the critical value; the electron is made to travel to the cathode in a circular path of smaller diameter.

View (D) of figure 2-22 shows how the magnetron plate current varies under the influence of the varying magnetic field. In view (A), the electron flow reaches the plate, so a large amount of plate current is flowing. However, when the critical field value is reached, as shown in view (B), 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, as shown in view (C), the plate current drops to zero. 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. These oscillations are caused by the currents induced electro statically by the moving electrons. The frequency is determined by the time it takes the electrons to travel from the cathode toward the plate and back again. A transfer of microwave energy to a load is made possible by connecting an external circuit between the cathode and the plate of the magnetron. Magnetron oscillators are divided into two classes:

NEGATIVE-RESISTANCE and ELECTRON-RESONANCE MAGNETRON OSCILLATORS.
A negative-resistance magnetron oscillator is operated by a static negative resistance between its electrodes. This oscillator has a frequency equal to the frequency of the tuned circuit connected to the tube. An electron-resonance magnetron oscillator is operated by the electron transit time required for electrons to travel from cathode to plate. This oscillator is capable of generating very large peak power outputs at frequencies in the thousands of megahertz. Although its average power output over a period of time is low, it can provide very high-powered oscillations in short bursts of pulses.