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# Microwave Power Tubes

## 6.1 Introduction

Microwave power tubes span a wide range of applications, operating at frequencies from 300 MHz to 300 GHz with output powers from a few hundred watts to more than 10 MW. Applications range from the familiar to the exotic. The following devices are included under the general description of microwave power tubes:

- Klystron, including the *reflex* and *multicavity* klystron
- *Multistage depressed collector* (MSDC) klystron
- *Inductive output tube* (IOT)
- *Traveling wave tube* (TWT)
- *Crossed-field tube*
- *Coaxial magnetron*
- *Gyrotron*
- *Planar triode*
- High-frequency tetrode
- *Diacrode*

This wide variety of microwave devices has been developed to meet a broad range of applications. Some common uses include:

- UHF-TV transmission
- Shipboard and ground-based radar
- Weapons guidance systems
- *Electronic countermeasure* (ECM) systems
- Satellite communications
- Tropospheric scatter communications

- Fusion research

As new applications are identified, improved devices are designed to meet the needs. Microwave power tube manufacturers continue to push the limits of frequency, operating power, and efficiency. Microwave technology, therefore, is an evolving science. [Figure 6.1](#) charts device type as a function of operating frequency and power output.

Two principal classes of microwave vacuum devices are in common use today:

- *Linear-beam* tubes
- *Crossed-field* tubes

Each class serves a specific range of applications. In addition to these primary classes, some power grid tubes also are used at microwave frequencies.

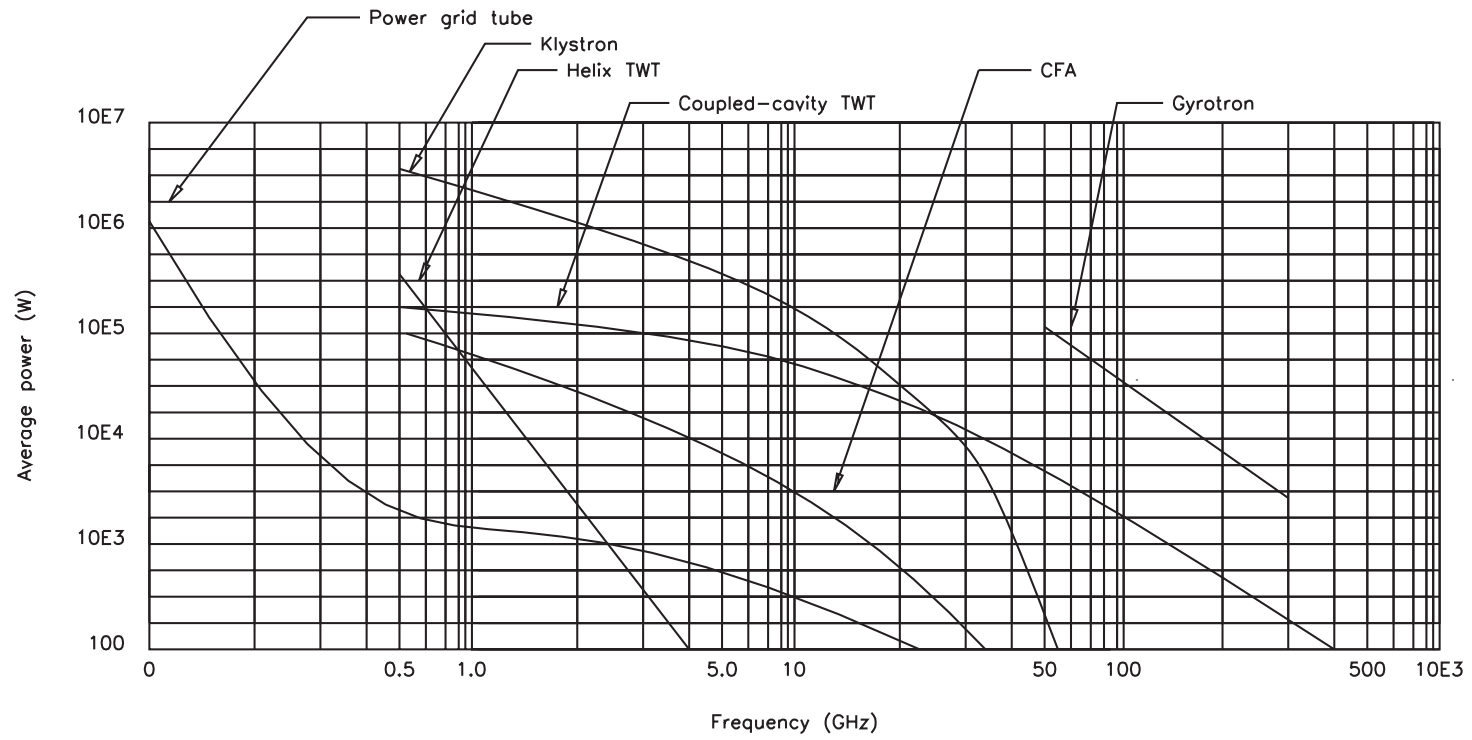
### 6.1.1 Linear-Beam Tubes

In a linear-beam tube, as the name implies, the electron beam and the circuit elements with which it interacts are arranged linearly. The major classifications of linear-beam tubes are shown in [Figure 6.2](#). In such a device, a voltage applied to an anode accelerates electrons drawn from a cathode, creating a beam of kinetic energy. Power supply potential energy is converted to kinetic energy in the electron beam as it travels toward the microwave circuit. A portion of this kinetic energy is transferred to microwave energy as RF waves slow down the electrons. The remaining beam energy is either dissipated as heat or returned to the power supply at the collector. Because electrons will repel one another, there usually is an applied magnetic focusing field to maintain the beam during the interaction process. The magnetic field is supplied either by a solenoid or permanent magnets. [Figure 6.3](#) shows a simplified schematic of a linear-beam tube.

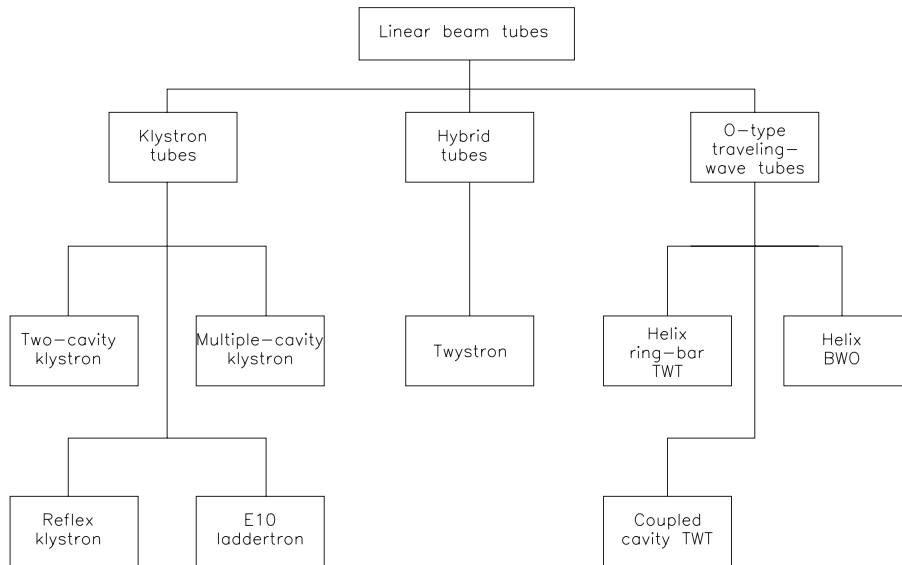
### 6.1.2 Crossed-Field Tubes

The magnetron is the pioneering device of the family of crossed-field tubes. The family tree of this class of devices is shown in [Figure 6.4](#). Although the physical appearance differs from that of linear-beam tubes, which are usually circular in format, the major difference is in the interaction physics that requires a magnetic field at right angles to the applied electric field. Whereas the linear-beam tube sometimes requires a magnetic field to maintain the beam, the crossed-field tube always requires a magnetic focusing field.

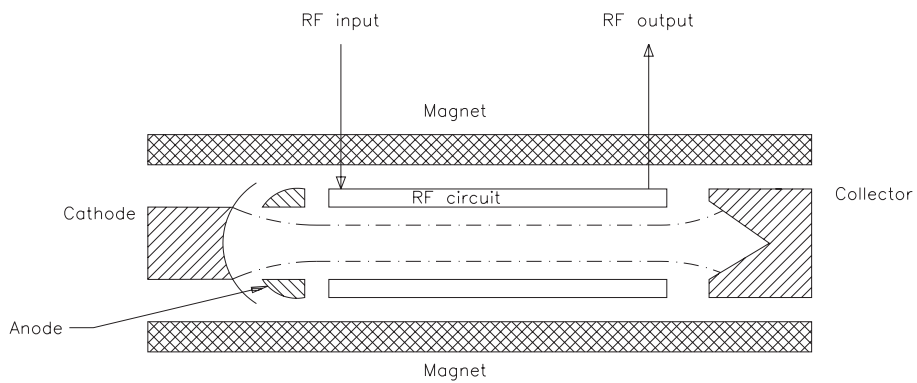
[Figure 6.5](#) shows a cross section of the magnetron, including the magnetic field applied perpendicular to the cathode-anode plane. The device is basically a diode with the anode composed of a plurality of resonant cavities. The interaction between the electrons emitted from the cathode and the crossed electric and magnetic fields produces a series of space-charge spokes that travel around the anode-cathode space in a manner that transfers energy to the RF signal supported by the multicavity circuit. The mechanism is highly efficient.



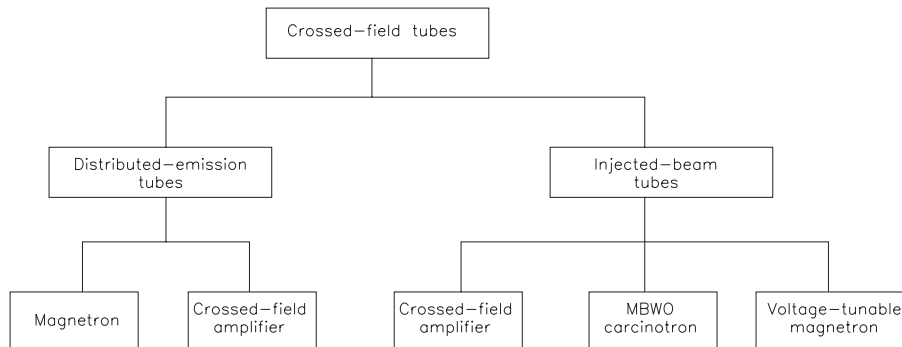
**Figure 6.1** Microwave power tube type as a function of frequency and output power.



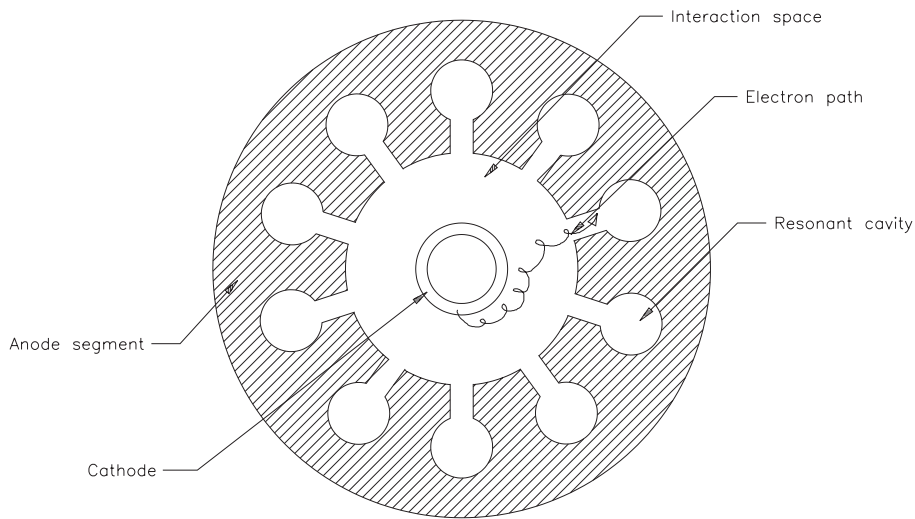
**Figure 6.2** Types of linear-beam microwave tubes.



**Figure 6.3** Schematic diagram of a linear-beam tube.



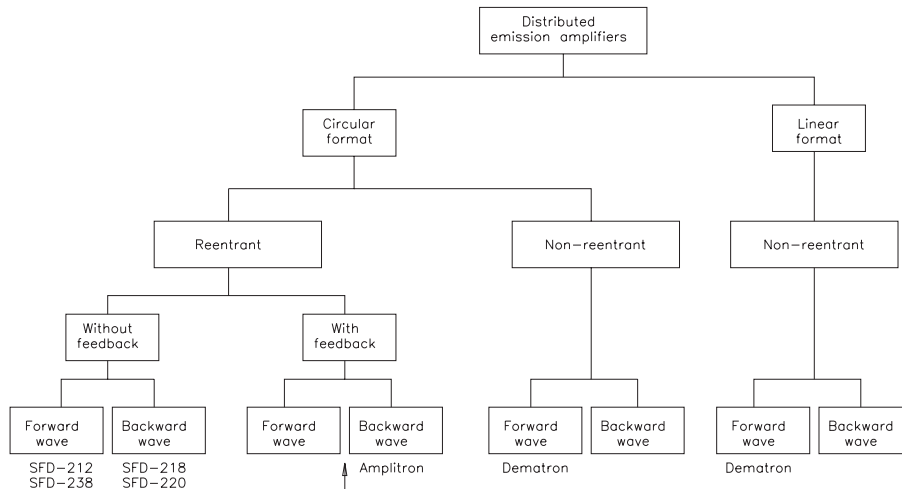
**Figure 6.4** Types of crossed-field microwave tubes.



**Figure 6.5** Magnetron electron path looking down into the cavity with the magnetic field applied.

### Crossed-Field Amplifiers

Figure 6.6 shows the family tree of the crossed-field amplifier (CFA). The configuration of a typical present-day distributed emission amplifier is similar to that of the magnetron except that the device has an input for the introduction of RF energy into the circuit. Current is obtained primarily by secondary emission from the negative



**Figure 6.6** Family tree of the distributed emission cross-field amplifier (CFA).

electrode that serves as a cathode throughout all or most of the interaction space. The earliest versions of this tube type were called *amplitrons*.

The CFA is deployed in radar systems operating from UHF to the Ku-band, and at power levels up to several megawatts. In general, bandwidth ranges from a few percent to as much as 25 percent of the center frequency.

## 6.2 Grid Vacuum Tubes

The physical construction of a vacuum tube causes the output power and available gain to decrease with increasing frequency. The principal limitations faced by grid-based devices include the following:

- Physical size. Ideally, the RF voltages between electrodes should be uniform, but this condition cannot be realized unless the major electrode dimensions are significantly less than  $1/4$  wavelength at the operating frequency. This restriction presents no problems at VHF, but as the operating frequency increases into the microwave range, severe restrictions are placed on the physical size of individual tube elements.
- Electron transit time. Interelectrode spacing, principally between the grid and the cathode, must be scaled inversely with frequency to avoid problems associated with electron transit time. Possible adverse conditions include: 1) excessive loading of the drive source, 2) reduction in power gain, 3) back-heating of the cathode as a result of electron bombardment, and 4) reduced conversion efficiency.

- Voltage standoff. High-power tubes operate at high voltages. This presents significant problems for microwave vacuum tubes. For example, at 1 GHz the grid-cathode spacing must not exceed a few mils. This places restrictions on the operating voltages that may be applied to the individual elements.
- Circulating currents. Substantial RF currents may develop as a result of the inherent interelectrode capacitances and stray inductances/capacitances of the device. Significant heating of the grid, connecting leads, and vacuum seals may result.
- Heat dissipation. Because the elements of a microwave grid tube must be kept small, power dissipation is limited.

Still, a number of grid-based vacuum tubes find applications at high frequencies. For example, planar triodes are available that operate at several gigahertz, with output powers of 1 to 2 kW in pulsed service. Efficiency (again for pulsed applications) ranges from 30 to 60 percent, depending on the frequency.

### 6.2.1 Planar Triode

A cross-sectional diagram of a planar triode is shown in [Figure 6.7](#). The envelope is made of ceramic, with metal members penetrating the ceramic to provide for connection points. The metal members are shaped either as disks or as disks with cylindrical projections.

The cathode is typically oxide-coated and indirectly heated. The key design objective for a cathode is high emission density and long tube life. Low-temperature emitters are preferred because high cathode temperatures typically result in more evaporation and shorter life.

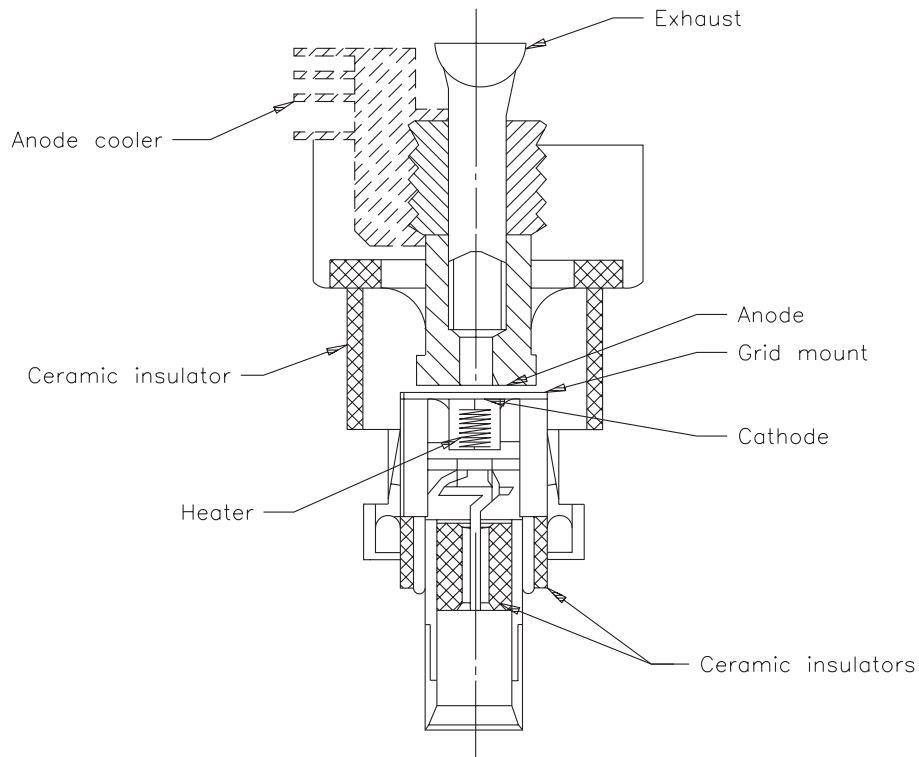
The grid of the planar triode is perhaps the greatest design challenge for tube manufacturers. Close spacing of small-sized elements is needed, at tight tolerances. Good thermal stability also is required, because the grid is subjected to heating from currents in the element itself, plus heating from the cathode and bombardment of electrons from the cathode.

The anode, usually made of copper, conducts the heat of electron bombardment to an external heat sink. Most planar triodes are air-cooled.

Planar triodes designed for operation at 1 GHz and above are used in a variety of circuits. The grounded-grid configuration is most common. The plate resonant circuit is cavity-based, using waveguide, coaxial line, or stripline. Electrically, the operation of the planar triode is much more complicated at microwave frequencies than at low frequencies. [Figure 6.8a](#) compares the elements at work for a grounded-grid amplifier operating at low frequencies and [Figure 6.8b](#) compares the situation at microwave frequencies. The equivalent circuit is made more complex by:

- Stray inductance and capacitance of the tube elements
- Effects of the tube contact rings and socket elements
- Distributed reactance of cavity resonators and the device itself





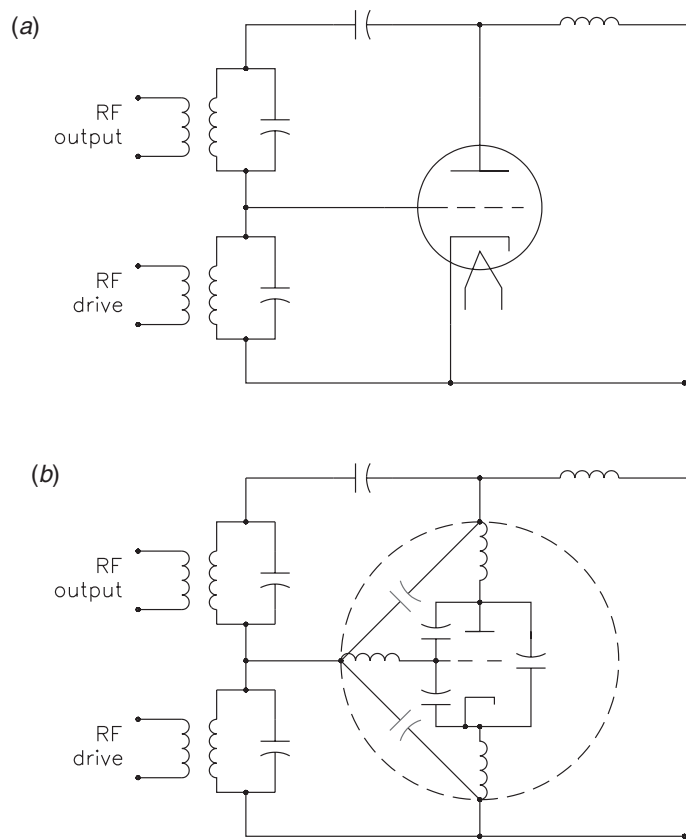
**Figure 6.7** Cross section of a 7289 planar triode.

- Electron transit-time effects, which result in resistive loading and phase shifts

Reasonable gains of 5 to 10 dB may be achieved with a planar triode. Increased gain is available by cascading stages. Interstage coupling may consist of waveguide or coaxial-line elements. Tuning is accomplished by varying the cavity inductance or capacitance. Additional bandwidth is possible by stagger tuning of cascaded stages.

### 6.2.2 High-Power UHF Tetrode

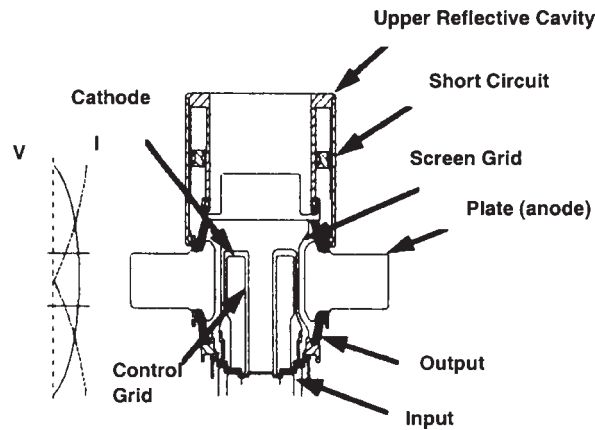
New advancements in vacuum tube technology have permitted the construction of high-power UHF transmitters based on tetrodes. Such devices are attractive because they inherently operate in a relatively efficient class AB mode. UHF tetrodes operating at high power levels provide essentially the same specifications, gain, and efficiency as tubes operating at lower powers. The anode power supply is much lower in voltage than the collector potential of a klystron- or IOT-based system (8 kV is common). Also, the tetrode does not require a focusing magnet system.



**Figure 6.8** Grounded-grid equivalent circuits: (a) low-frequency operation, (b) microwave-frequency operation. The cathode-heating and grid-bias circuits are not shown.

Efficient removal of heat is the key to making a tetrode practical at high power levels. Such devices typically use water or vapor-phase cooling. Air cooling at such levels is impractical because of the fin size that would be required. Also, the blower for the tube would have to be quite large, reducing the overall transmitter ac-to-RF efficiency.

Another drawback inherent in tetrode operation is that the output circuit of the device appears electrically in series with the input circuit and the load [1]. The parasitic reactance of the tube elements, therefore, is a part of the input and output tuned circuits. It follows, then, that any change in the operating parameters of the tube as it ages can affect tuning. More importantly, the series nature of the tetrode places stringent limitations on internal element spacings and the physical size of those elements in order to minimize the electron transit time through the tube vacuum space. It is also fair to point out, however, the tetrode's input-to-output circuit characteristic has at least one advantage: power delivered to the input passes through the tube and contributes to the total power output of the transmitter. Because tetrodes typically exhibit low gain compared



**Figure 6.9** Cutaway view of the tetrode (*left*) and the Diacrode (*right*). Note that the RF current peaks above and below the Diacrode center while on the tetrode there is only one peak at the bottom. (After [2].)

to a klystron-based device, significant power can be required at the input circuit. The pass-through effect, therefore, contributes to the overall operating efficiency of the transmitter.

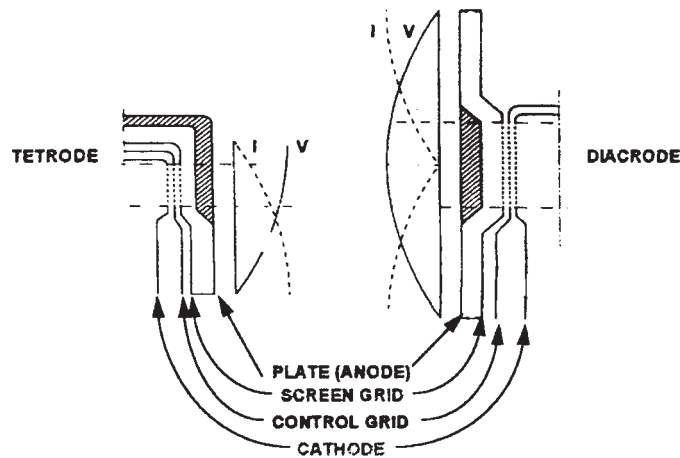
The expected lifetime of a tetrode in UHF service is usually shorter than a klystron of the same power level. Typical lifetimes of 8,000 to 15,000 hours have been reported. Intensive work, however, has led to products that offer higher output powers and extended operating lifetime, while retaining the benefits inherent in tetrode devices.

### 6.2.3 Diacrode

The *Diacrode* (Thomson) is a promising adaptation of the high-power UHF tetrode. The operating principle of the Diacrode is basically the same as that of the tetrode. The anode current is modulated by an RF drive voltage applied between the cathode and the power grid. The main difference is in the position of the active zones of the tube in the resonant coaxial circuits, resulting in improved reactive current distribution in the electrodes of the device.

Figure 6.9 compares the conventional tetrode with the Diacrode. The Diacrode includes an electrical extension of the output circuit structure to an external cavity [2]. The small dc-blocked cavity rests on top of the tube, as illustrated in Figure 6.10.

The cavity is a quarter-wave transmission line, as measured from the top of the cavity to the vertical center of the tube. The cavity is short-circuited at the top, reflecting an open circuit (current minimum) at the vertical center of the tube and a current maximum at the base of the tube, like the conventional tetrode, and a second current maximum above the tube at the cavity short-circuit.



**Figure 6.10** The elements of the Diacrode, including the upper cavity. Double current, and consequently, double power, is achieved with the device because of the current peaks at the top and bottom of the tube, as shown. (After [2].)

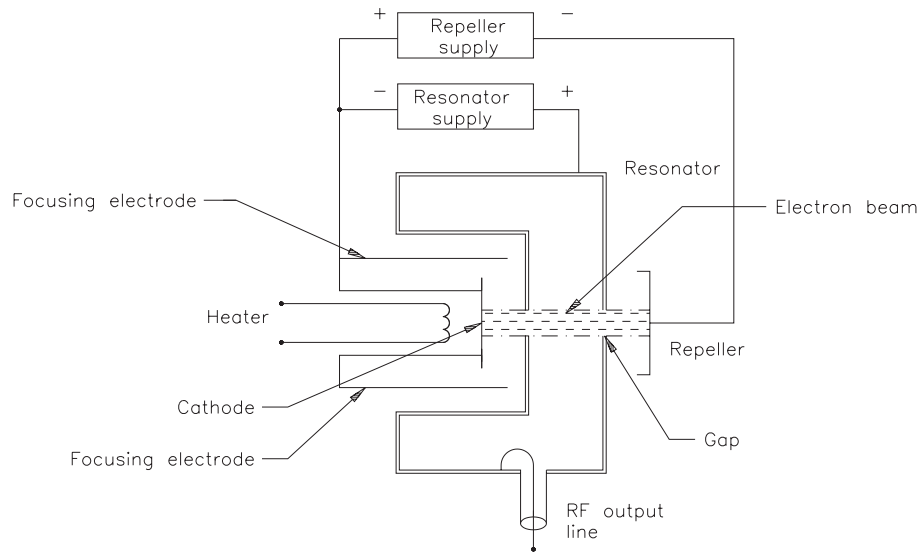
With two current maximums, the RF power capability of the Diacrode is double that of the equivalent tetrode, while the element voltages remain the same. All other properties and aspects of the Diacrode are basically identical to the TH563 high-power UHF tetrode (Thomson), upon which the Diacrode is patterned.

Some of the benefits of such a device, in addition to the robust power output available, is the low high-voltage requirements (low relative to a klystron/IOT-based system, that is), small size, and simple replacement procedures. On the downside, there is little installed service lifetime data at this writing because the Diacrode is relatively new to the market.

### 6.3 Klystron

The klystron is a *linear-beam* device that overcomes the transit-time limitations of a grid-controlled tube by accelerating an electron stream to a high velocity before it is modulated. Modulation is accomplished by varying the velocity of the beam, which causes the drifting of electrons into *bunches* to produce RF *space current*. One or more cavities reinforce this action at the operating frequency. The output cavity acts as a transformer to couple the high-impedance beam to a low-impedance transmission line. The frequency response of a klystron is limited by the impedance-bandwidth product of the cavities, but may be extended through stagger tuning or the use of multiple-resonance filter-type cavities.

The klystron is one of the primary means of generating high power at UHF and above. Output powers for multicavity devices range from a few thousand watts to 10



**Figure 6.11** Schematic representation of a reflex klystron.

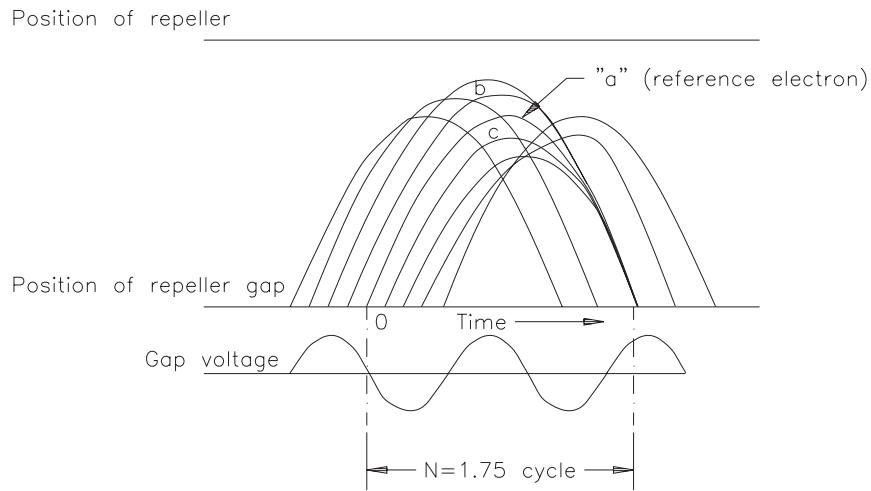
MW or more. The klystron provides high gain and requires little external support circuitry. Mechanically, the klystron is relatively simple. It offers long life and requires minimal routine maintenance.

### 6.3.1 Reflex Klystron

The reflex klystron uses a single-cavity resonator to modulate the RF beam and extract energy from it. The construction of a reflex klystron is shown in [Figure 6.11](#). In its basic form, the tube consists of the following elements:

- A cathode
- Focusing electrode at cathode potential
- Coaxial line or reentrant-type cavity resonator, which also serves as an anode
- *Repeller* or *reflector* electrode, which is operated at a moderately negative potential with respect to the cathode

The cathode is so shaped that, in relation to the focusing electrode and anode, an electron beam is formed that passes through a gap in the resonator, as shown in the figure, and travels toward the repeller. Because the repeller has a negative potential with respect to the cathode, it turns the electrons back toward the anode, where they pass through the anode gap a second time. By varying the applied voltage on the reflector



**Figure 6.12** Position-time curves of electrons in the anode-repeller space, showing the tendency of the electrons to bunch around the electron passing through the anode at the time when the alternating gap voltage is zero and becoming negative.

electrode, phasing of the beam can be varied to produce the desired oscillating mode and to control the frequency of oscillation.

The variation of position with time for electrons in the anode-repeller space is illustrated in Figure 6.12. Path *a* corresponds to an electron that emerges from the anode with a velocity corresponding to the anode voltage. This electron follows a parabolic path, as shown, determined by the electric field in the anode-repeller space.

Operation of the reflex klystron can best be understood by examining the movement of electrons inside the device. Assume that oscillations exist in the resonator so that an alternating voltage develops across the gap. Assume further that the electron corresponding to path *a* passed through the gap at the instant that this alternating voltage across the gap was zero and becoming negative. An electron passing through the gap just before electron *a* will encounter an accelerating voltage across the gap and, therefore, will emerge from the anode with greater velocity than the first or *reference* electron. This second electron, accordingly, penetrates farther toward the repeller against the retarding field and, as a result, takes longer to return to the anode. Consequently, this electron follows path *b*, as shown in Figure 6.12, and tends to arrive at the anode on its return path at the same time as the reference electron because its earlier start is more or less compensated for by increased transit time. In a similar manner, an electron passing through the anode gap slightly later than the reference electron will encounter a negative or retarding field across the gap, and so will emerge from the anode with less velocity than the electron that follows path *a*. This third electron will then follow trajectory *c* and return to the anode more quickly than electron *a*. Electron *c*, therefore, tends to return to the anode at about the same time as electron *a*, because the later start of electron *c* is compensated for by the reduced transit time.

This variation with time of the velocity of electrons emerging from the anode is termed *velocity modulation*. The effect of this phenomenon can be seen in [Figure 6.12](#) to cause a *bunching* of electrons about the electron that passed through the gap when the resonator voltage was zero and becoming negative. This bunching causes the electrons that are returned toward the anode by the repeller to pass through the anode gap in bursts or pulses, one each cycle. When these pulses pass through the gap at such a time that the electrons in the pulse are slowed as a result of the alternating voltage existing across the gap at the instant of their return passage, energy will be delivered to the oscillations in the resonator, thereby assisting in maintaining the oscillations. This condition corresponds to a transit time  $N$  from the resonator toward the repeller and back to the resonator of approximately:

$$N = n + \frac{3}{4} \tag{6.1}$$

Where:

$n$  = an integer (including zero)

The transit time in the anode-repeller space in any particular case depends upon the following:

- The anode voltage
- Repeller voltage
- Geometry of the anode-repeller space

The extent of the bunching action that takes place when the transit time of the reference electron has the correct value for sustaining oscillations is determined by the following:

- The amplitude of the alternating voltage across the resonator gap in relation to the anode and repeller voltage
- The geometry of the repeller space

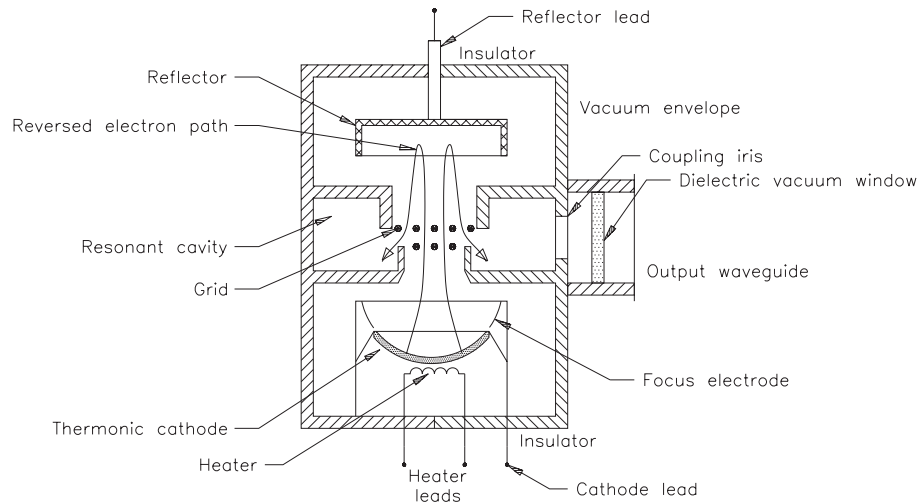
The reflex klystron typically includes a grid to concentrate the electric field so that it may efficiently couple to the electron beam. Such a device is illustrated in [Figure 6.13](#).

The reflex klystron may be used as a local oscillator, low-power FM transmitter, or test signal source. Reflex tubes are used primarily from 4 to 40 GHz. Power outputs of 1 W or less are common.

The reflex tube is the only klystron in which *beam feedback* is used to produce output energy. In klystrons with more than one cavity, the electron beam passes through each cavity in succession.

### 6.3.2 The Two-Cavity Klystron

The two-cavity klystron operates on the same bunching principle as the reflex klystron, but incorporates two cavities connected by a *drift tube*. [Figure 6.14](#) shows a cross section of a classic device. The heater/cathode element (shown as A in the fig-



**Figure 6.13** Schematic cross section of a reflex klystron oscillator.

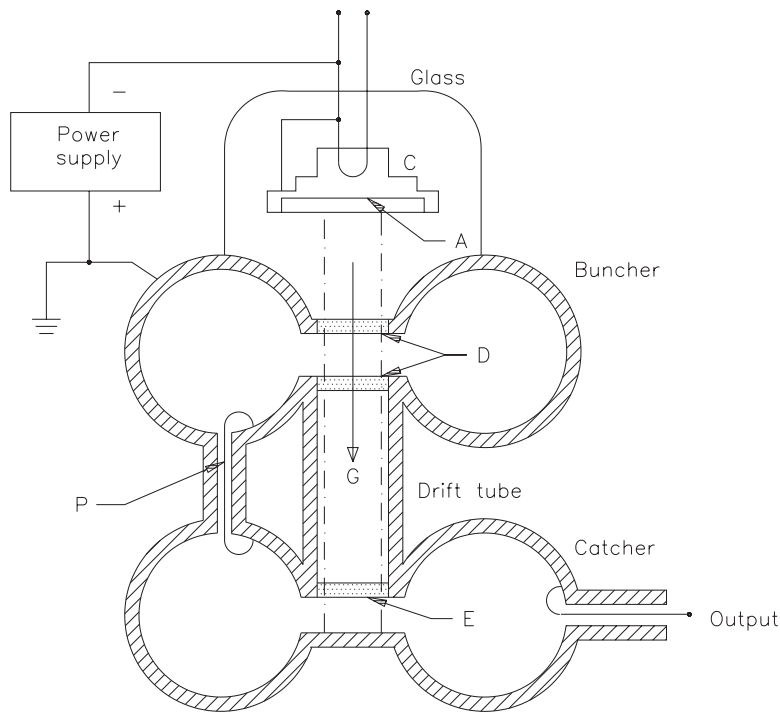
ure) produces an electron beam in conjunction with a focusing electrode. The route taken by the electrons is as follows:

- The beam passes through grid elements D in the side of a reentrant cavity resonator (the buncher).
- The beam then passes through the drift tube, which is at the same electrical potential as the buncher.
- Finally, the beam enters a second resonator termed the *collector*, which is provided with a grid E.

The cathode and its associated focusing electrode are maintained at a high negative potential with respect to the remaining part of the structure, all of which is at the same dc potential. The entire arrangement illustrated in the figure is enclosed in a vacuum.

The operational principles of the two-cavity klystron are similar in nature to those of the reflex klystron. Assume, first, that oscillations exist in the buncher so that an alternating voltage is present across the gap D. When this voltage is zero but just becoming positive, an electron passing through the buncher travels through the grids D, down the drift tube, and into the collector resonator with unchanged velocity. However, an electron that passes through the buncher slightly later receives acceleration while passing through, because of the positive alternating field that it encounters between grids D, and enters the drift tube with increased velocity. This later electron, therefore, tends to overtake the earlier electron. Similarly, an electron that arrives at the buncher slightly





**Figure 6.14** Cross section of a classic two-cavity klystron oscillator.

earlier than the first (reference electron) encounters a field between grids D that opposes its motion. Hence, this early electron enters the drift tube with reduced velocity and tends to drop back and be overtaken by the reference electron.

As a result of these actions, the electrons bunch together as they travel down the drift tube. This effect is more pronounced at certain distances from the buncher. If the collector is located at a distance where the bunching is pronounced, the electrons enter the element in pulses, one pulse per cycle.

With proper adjustment, the amount of power required to produce the bunching effect is relatively small compared with the amount of energy delivered by the electron beam to the collector. As a result, the klystron operates as an amplifying device.

### The Two-Cavity Klystron Oscillator

The two-cavity klystron oscillator is designed for applications requiring moderate power (up to 100 W), stable frequency output, and low sideband noise. The device has a coupling iris on the wall between the two cavities. The tube can be frequency-modulated by varying the cathode voltage about the center of the oscillating mode. Although it is more efficient and powerful than the reflex klystron, the two-cavity kly-

stron requires more modulator power. The two-cavity klystron typically is used in Doppler radar systems.

### **The Two-Cavity Klystron Amplifier**

Similar in design to the two-cavity oscillator, the two-cavity klystron amplifier provides limited power output (10 W or less) and moderate gain (about 10 dB). A driving signal is coupled into the input cavity, which produces velocity modulation of the beam. After the drift space, the density-modulated beam induces current in the output resonator. Electrostatic focusing of the beam is common.

The two-cavity klystron finds only limited applications because of its restrictions on output power and gain. For many applications, solid-state amplifiers are a better choice.

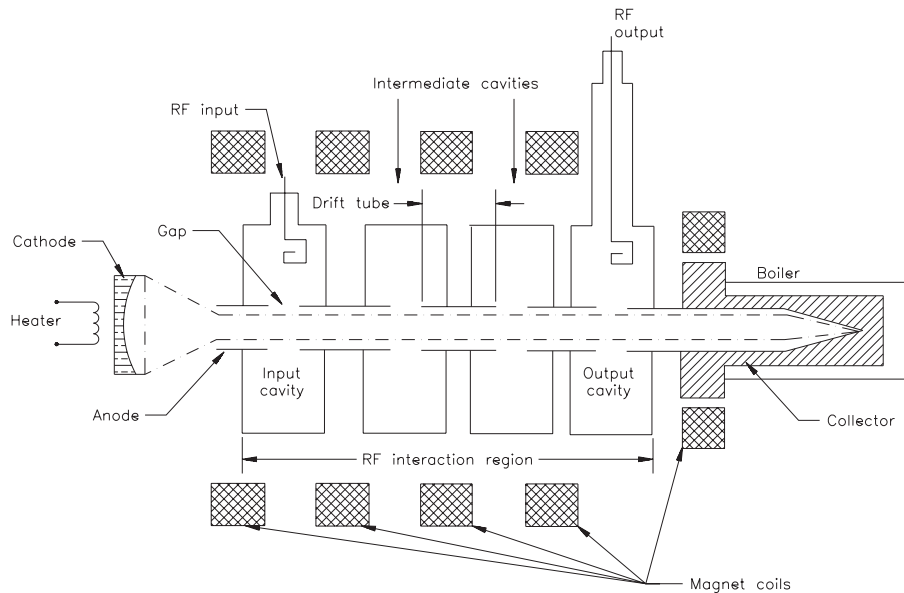
### **6.3.3 The Multicavity Klystron**

The multicavity klystron is an important device for amplifying signals to high power levels at microwave frequencies [3]. Each cavity tuned to the operating frequency adds about 20 dB gain to the 10 dB gain offered by the basic two-cavity klystron amplifier. Overall gains of 60 dB are practical. Cavities may be tuned to either side of resonance to broaden the operating bandwidth of the device. Klystrons with up to eight cavities have been produced. Operating power for continuous wave klystrons ranges up to 1 MW per device, and as much as 50 MW per device for pulsed applications.

The primary physical advantage of the klystron over a grid-based power tube is that the cathode-to-collector structure is virtually independent of transit-time effects. Therefore, the cathode can be made large and the electron beam density kept low.

The operating frequency of a klystron may be fixed—determined by the mechanical characteristics of the tube and its cavities—or tunable. Cavities are tuned mechanically using one of several methods, depending on the operating power and frequency. Tuning is accomplished by changing the physical dimensions of the cavities using one or more of the following techniques:

- *Cavity wall deformation*, in which one wall of the cavity consists of a thin diaphragm that is moved in and out by a tuning mechanism. About 3 percent frequency shift may be accomplished using this method, which varies the inductance of the cavity.
- *Movable cavity wall*, in which one wall of the cavity is moved in or out by a tuning mechanism. About 10 percent frequency shift is possible with this approach, which varies the inductance of the cavity.
- *Paddle element*, in which an element inside the cavity moves perpendicularly to the beam and adds capacitance across the interaction gap. A tuning range of about 25 percent is provided by this approach.
- *Combined inductive-capacitive tuning*, which uses a combination of the previous methods. Tuning variations of 35 percent are possible.



**Figure 6.15** Principal elements of a klystron.

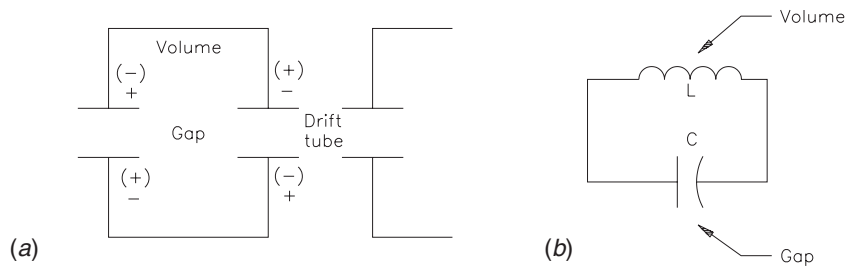
Each of these tuning methods may be used whether the cavity is inside or outside the vacuum envelope of the tube. Generally speaking, however, tubes that use external cavities provide more adjustment range, usually on the order of 35 percent. Bandwidth may be increased by stagger tuning of the cavities, at the expense of gain.

High conversion efficiency requires the formation of electron bunches, which occupy a small region in velocity space, and the formation of *interbunch regions* with low electron density. The latter is particularly important because these electrons are phased to be accelerated into the collector at the expense of the RF field. Studies show that the energy loss as a result of an electron accelerated into the collector may exceed the energy delivered to the field by an equal but properly phased electron. Therein lies a key in improving the efficiency of the klystron: Recover a portion of this wasted energy.

Klystrons are cooled by air or liquid for powers up to 5 kW. Tubes operating in excess of 5 kW are usually water- or vapor-cooled.

### Operating Principles

A high-velocity electron beam emitted from the cathode passes through the anode and into the RF interaction region, as shown in [Figure 6.15](#) [3]. An external magnetic field is employed to prevent the beam from spreading as it passes through the tube. At the other end of the device, the electron beam impinges on the collector electrode, which dissipates the beam energy and returns the electron current to the beam power supply.

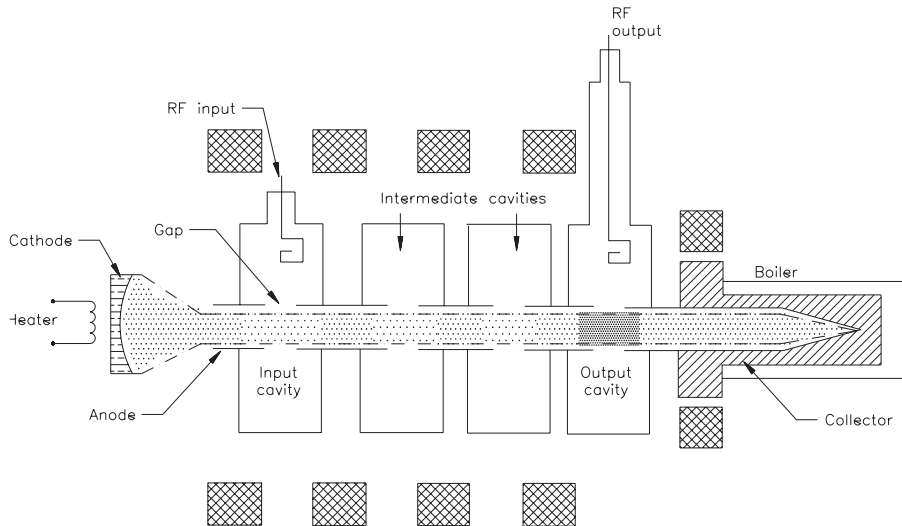


**Figure 6.16** Klystron cavity: (a) physical arrangement, (b) equivalent circuit.

The RF interaction region, where amplification occurs, contains resonant cavities and field-free drift spaces. The first resonant cavity encountered by an electron in the beam (the input cavity) is excited by the microwave signal to be amplified, and an alternating voltage of the signal frequency is developed across the gap. This action can be best explained by drawing an analogy between a resonant cavity and a conventional parallel resonant  $LC$  circuit (see Figure 6.16). The cavity gap corresponds to the capacitor, and the volume of the cavity to the inductor. If the cavity is of the correct physical dimensions, it will resonate at the desired microwave frequency. At resonance, opposite sides of the gap become alternately positive and negative at a frequency equal to the microwave input signal frequency.

An electron passing through the gap when the voltage across the gap is zero continues with unchanged velocity along the drift tube toward the next cavity gap; this electron is the *reference electron*. An electron passing through the same gap slightly later is accelerated by the positive field at the gap. This electron speeds up and tends to overtake the reference electron ahead of it in the drift tube. However, an electron that passes through the gap slightly ahead of the reference electron encounters a negative field and is slowed down. This electron tends to fall back toward the following reference electron. As a result of passing the alternating field of the input-cavity gap, the electrons gradually bunch together as they travel down the drift tube, as illustrated in Figure 6.17. Because electrons approach the input-cavity gap with equal velocities and emerge with different velocities, which are a function of the microwave signal, the electron beam is said to be velocity-modulated. As the electrons travel down the drift tube, bunching develops, and the density of electrons passing a given point varies cyclically with time. This bunching is identical in nature to the action in a two-cavity klystron, discussed in Section 6.3.2.

The modulation component of the beam current induces current in each of the following cavities. Because each cavity is tuned near resonance, the resulting increase in field at each gap produces successively better-defined electron bunches and, consequently, amplification of the input signal. The RF energy produced in this interaction with the beam is extracted from the beam and fed into a coaxial or waveguide transmission line by means of a coupling loop in the output cavity. The dc beam input power not converted to RF energy is dissipated in the collector.



**Figure 6.17** Bunching effect of a multicavity klystron.

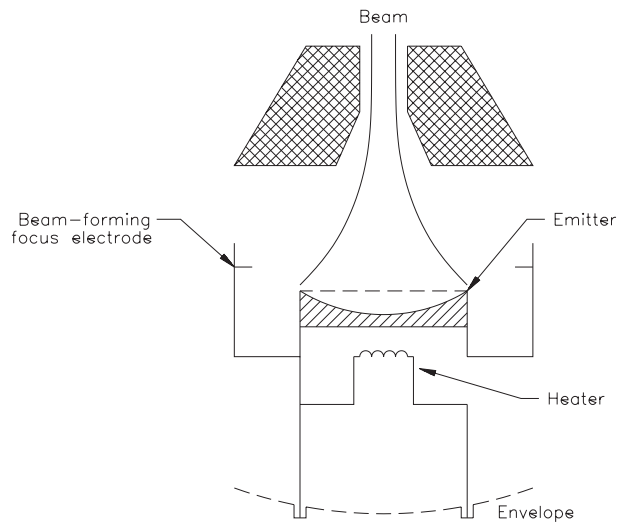
### Emission

The electron gun section of a klystron, shown in [Figure 6.18](#), consists of the following elements [3]:

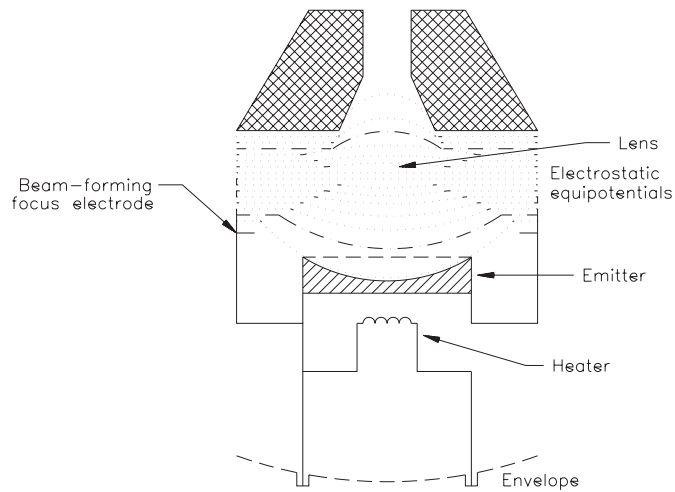
- A heater
- An emitter
- A beam-forming focusing electrode
- A modulating anode

When the emitter temperature is raised to the proper value by the heater, electrons are released from the emitter surface. The electrons are accelerated toward the modulating anode, which is at a positive potential with respect to the emitter. As the electrons travel between the emitter and the modulating anode, they are formed into a beam by the lens action of the focusing electrode and modulating anode. [Figure 6.19](#) shows how this lens is formed.

All cathodes have a specific optimum range of operating temperature. The temperature of the cathode must be sufficiently high to prevent variations in heater power from affecting the electron emission current (beam current) in the klystron. However, the temperature of the emitting surface must not be higher than necessary because excessive temperature can shorten emission life. [Figure 6.20](#) shows beam current (emission current) as a function of the emitter temperature, which varies directly with heater power. When the heater voltage ( $E_h$ ) is too low, the emitter will not be hot enough to

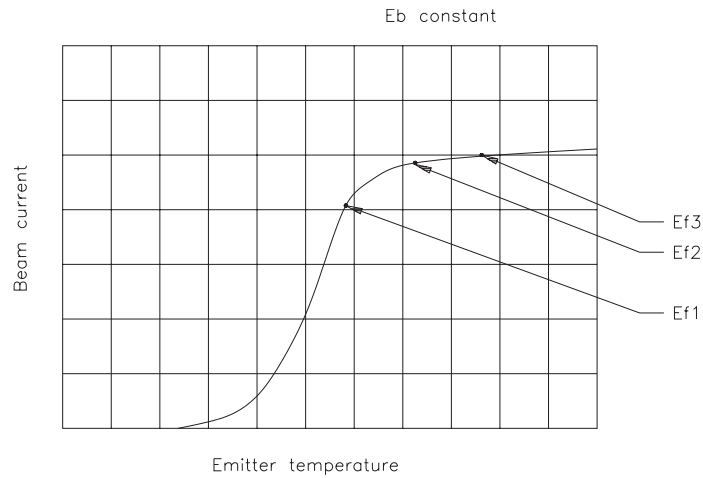


**Figure 6.18** Diode section of a klystron electron gun.



**Figure 6.19** Beam forming in the diode section of a klystron electron gun.

produce the desired beam current. In addition, even small variations in heater voltage will change the beam current significantly. With the proper heater voltage ( $E_{\rho}$ ), constant beam current will be maintained even with minor variations in heater voltage. The same is true for a higher heater voltage value ( $E_{\beta}$ ), but in this case the emitter temperature is greater than that needed for the desired beam current. Reduced tube life will re-



**Figure 6.20** Klystron beam-current variation as a function of emitter temperature.

sult. The correct value of heater voltage and/or heater current is included in the data shipped with each klystron.

### Modulating Anode

Because the modulating anode is electrically isolated from both the cathode and klystron body (the RF structure, between polepieces) the voltage applied to it provides a convenient means for controlling beam current independently of the beam voltage applied between the cathode and body, as shown in Figure 6.21. When the cathode is operated in the space-charge-limited region,  $E_{\rho_2}$  and  $E_{\rho_3}$  of Figure 6.20, the emission current will be a specific function of the applied voltage:

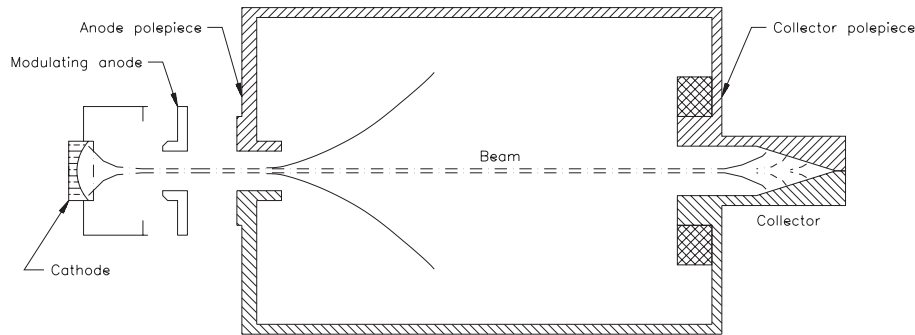
$$I_b = k E^{3/2} \quad (6.2)$$

Where:

$I_b$  = beam current in amps

$E$  = beam potential in volts

The constant  $k$  is a function of the geometry of the cathode-anode structure, and is termed *perveance*. Because the modulating anode is physically positioned between the RF structure (body) and the cathode, even if the full beam voltage is maintained between cathode and body, the actual beam current into the tube may be reduced at will by biasing the modulating anode to any voltage between cathode and body. Figure 6.22 shows the relationship between beam current and voltage described in the previous equation.



**Figure 6.21** Modulating-anode electrode in a multicavity klystron.

### Magnetic Field

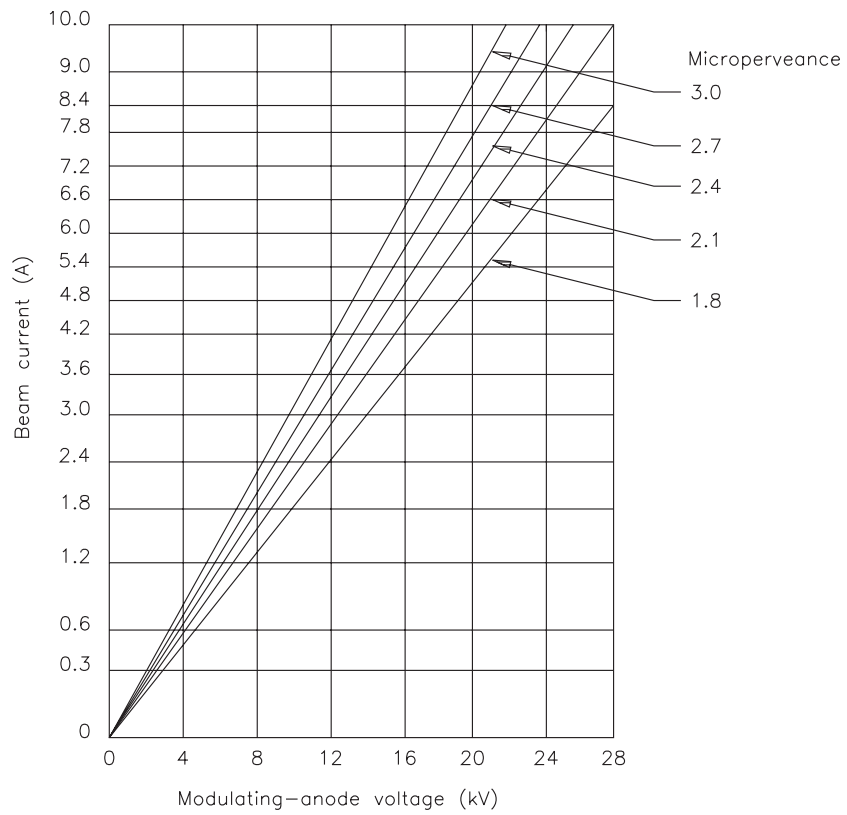
*Beam focusing* is used in multielement klystrons to keep the electron beam uniformly small. Focusing may be accomplished by one or more electrostatic *lenses* or external magnetic fields placed parallel to the beam. Magnetic focusing is the most common method. Permanent magnets are used at operating powers of about 5 kW or less. Electromagnets are used at higher powers.

Electromagnetic coils typically are placed around the klystron to develop the magnetic field along the axis of the RF circuit. This field controls the size of the electron beam and keeps it aligned with the drift tubes. [Figure 6.23](#) illustrates the beam-forming portion at the cathode end of the klystron and RF section, where the magnetic field is developed between two cylindrical disks (polepieces). The electron beam in this illustration is shown traveling two paths. One path shows the beam spreading out to points A; the other path shows the beam confined by the magnetic field to a constant size throughout the distance between polepieces. The beam spreads toward points A when the magnetic field is inadequate.

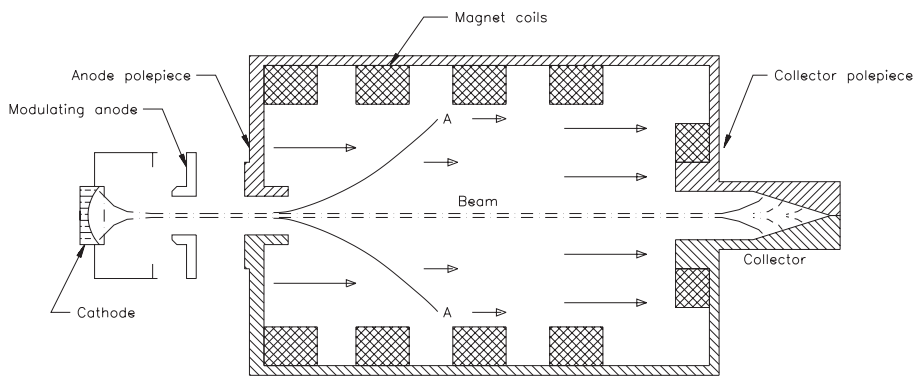
[Figure 6.24](#) shows the magnetic field pattern of a typical solenoid used for klystrons. When direct current passes through the magnetic coils, a magnetic field is generated along the axis of the tube. The strength of this field can be controlled by changing the current flow through the magnetic coils. The shape of the field is determined by polepiece geometry and winding distribution inside the solenoid. [Figure 6.25](#) illustrates the field pattern and the shape of the beam for a properly adjusted field.

[Figure 6.26](#) demonstrates how the beam of a klystron is distorted when an external magnetic material is placed near the RF circuit of the tube. Electrons in the beam will follow the bent magnetic field lines and may strike the walls of the drift tube. Klystron damage can result. Magnetic materials such as screwdrivers, wrenches, bolts, and nuts must not be left near the magnetic circuit or near the cathode or collector. Magnetic tools must not be used to tune a klystron.

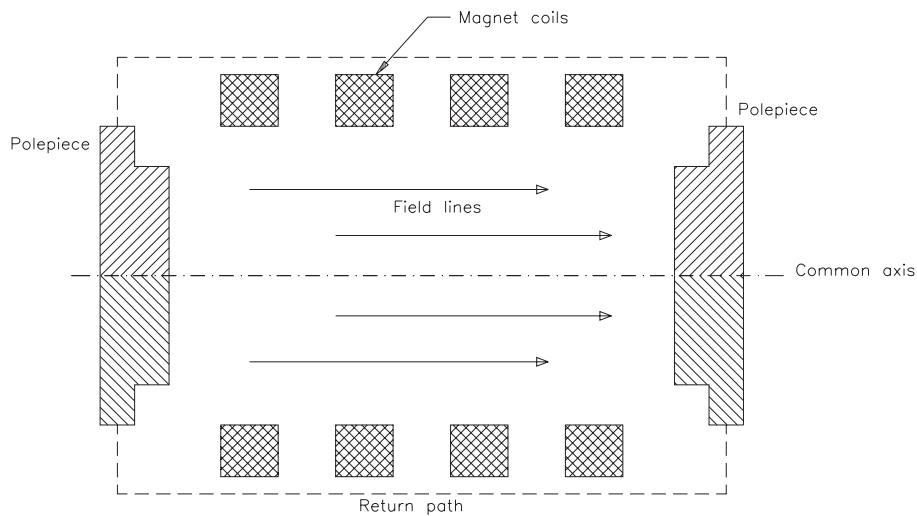




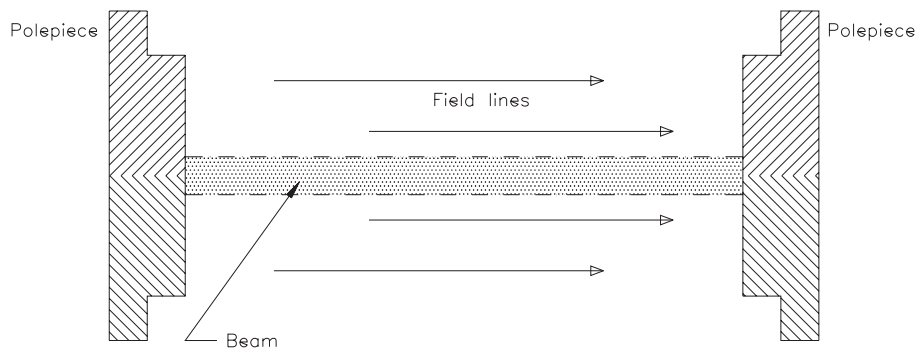
**Figure 6.22** Beam-current variation as a function of modulating-anode voltage.



**Figure 6.23** The effect of a magnetic field on the electron beam of a klystron.



**Figure 6.24** Field pattern of a klystron electromagnet.

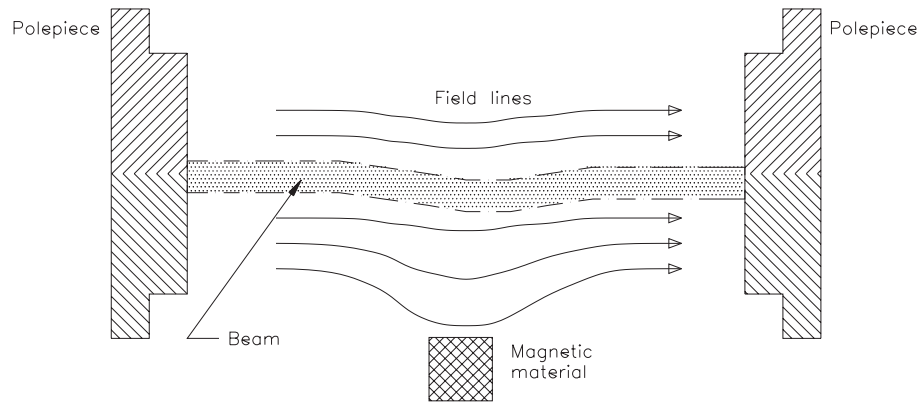


**Figure 6.25** Field pattern and beam shape in a properly adjusted magnetic field.

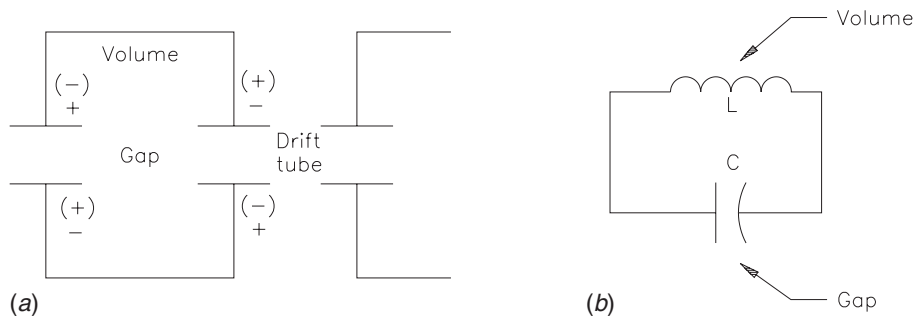
### RF Structure

The RF structure of a klystron amplifier consists of tunable resonant circuits (cavities) positioned along the axis of the electron beam. The electron beam traveling through the cavities provides the necessary coupling between each of the RF circuits.

The cavities of a klystron are high-frequency parallel resonant circuits constructed so that they provide an RF voltage across the capacitive component (gap), which interacts with the dc beam. [Figure 6.27a](#) illustrates the polarity near the drift-tube tips within a cavity excited by an alternating voltage of microwave signal frequency. [Figure 6.27b](#)



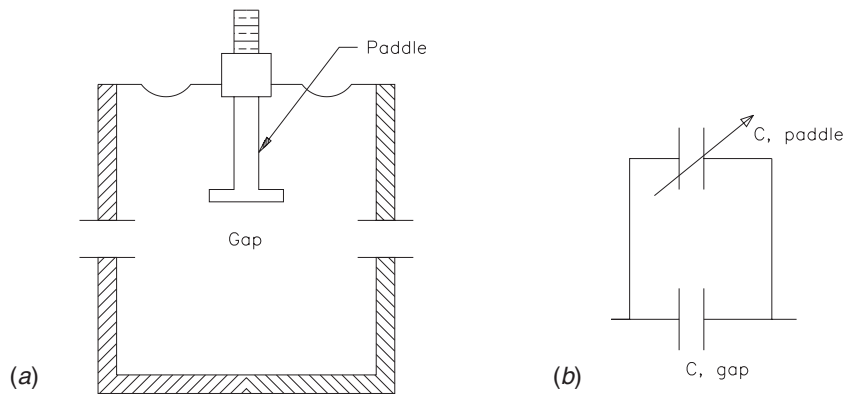
**Figure 6.26** Distortion of the field pattern and beam shape due to magnetic material in the magnetic field.



**Figure 6.27** Klystron cavity: (a) physical element, (b) equivalent electric circuit.

is the equivalent circuit of a simple cavity. To achieve circuit resonance, the inductive and capacitive reactances of each of the components must be equal. The reactance of each of the components shown in the figure can be measured separately. However, the reactances of the components within a klystron cavity are difficult to determine, because they cannot be measured individually. Therefore, the regions of voltage maxima or minima are used to define each component of a klystron cavity in the following way:

- The capacitance of a cavity is developed across the gap at the drift tubes where the voltage is at maximum.
- The inductance of a cavity is located in the outer volume of the cavity where the voltage is at minimum.



**Figure 6.28** Capacitance-tuned klystron cavity: (a) physical element, (b) equivalent circuit.

By defining each component of a cavity in these terms, it is easy to visualize changes in the volume as changes in inductance, and changes affecting the gap as changes in capacitance.

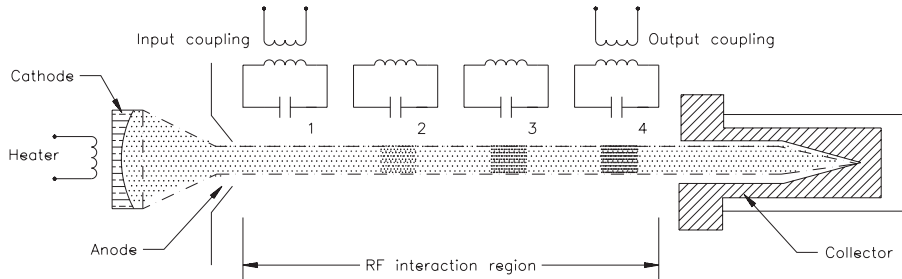
The resonant frequency of each cavity can be adjusted to the operating frequency of the RF generator. This can be accomplished in one of two ways:

- Change the inductance by changing the volume of the cavity.
- Change the capacitance of the drift-tube gaps.

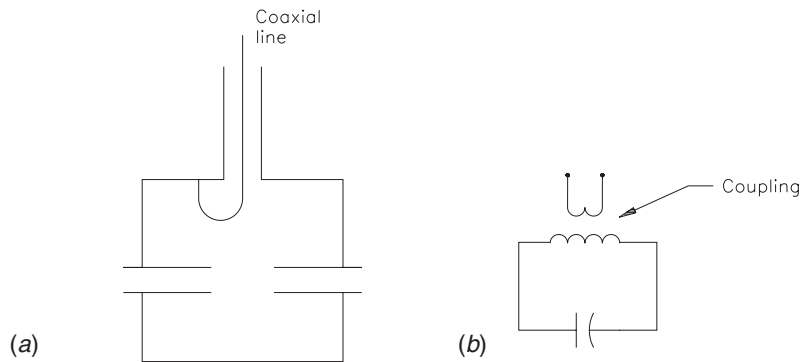
Figure 6.28 illustrates how the capacitance of the cavity gap can be modified by attaching a post to a thin-wall diaphragm with a paddle close to the drift-tube gap. In (a), the mechanical configuration of a cavity with this type of tuning is illustrated; (b) shows the equivalent circuit capacitance formed between the paddle and the drift tubes at the gap. Moving the paddle away from the drift tubes decreases the gap capacitance and increases the resonant frequency of the cavity.

Figure 6.29 shows a schematic diagram of the equivalent circuits of a four-cavity klystron. Circuit 1 is the input, and circuit 4 is the output. Figure 6.30a illustrates magnetic-loop coupling, where the RF energy is fed through a coaxial line with its center conductor inserted into the klystron cavity. The end of the center conductor is formed into a loop. This forms a simple one-turn transformer that couples RF energy into or out of the cavity through a coaxial transmission line. Figure 6.30b shows the equivalent circuit. The transformer formed by the loop and cavity is an impedance-matching device between the transmission line and the cavity.

Klystron cavities may be externally loaded to improve their instantaneous bandwidth characteristics. These loads lower the  $Q$  of the cavities slightly and thereby increase the bandwidth of the klystron.



**Figure 6.29** Schematic equivalent circuit of a four-cavity klystron.



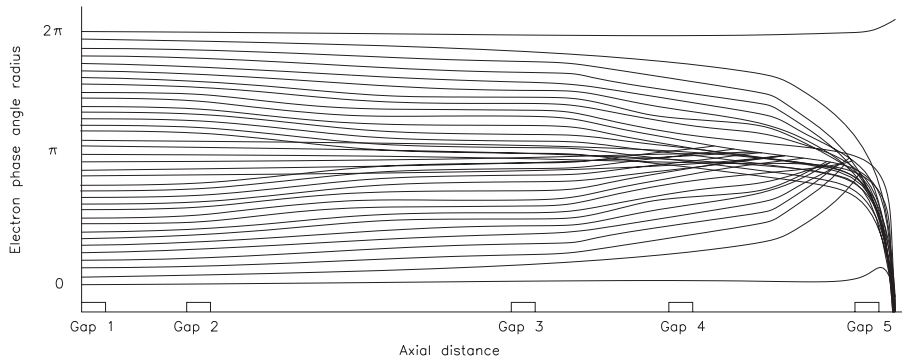
**Figure 6.30** Klystron loop coupling: (a) mechanical arrangement, (b) equivalent electric circuit.

### Phased Electron Operation

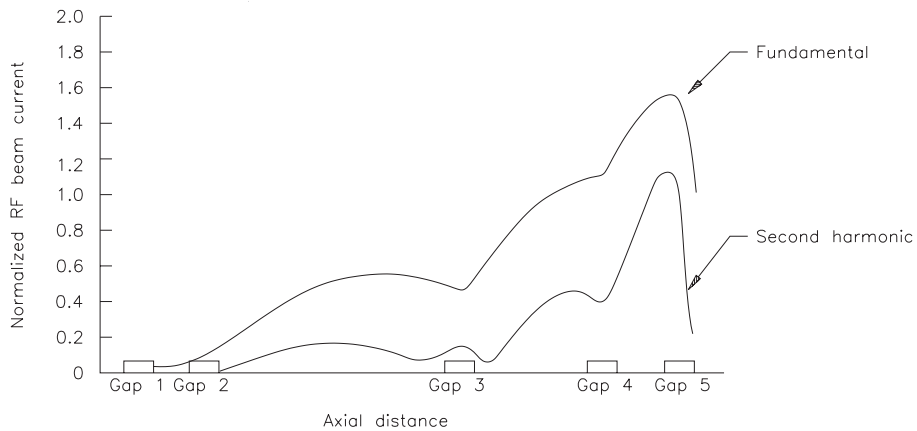
By properly phasing the second-harmonic fields of a klystron, a favorable electron density distribution pattern can be established at the output gap. The result is the generation of additional RF energy.

A phase-space diagram for a high-power klystron is shown in [Figure 6.31](#). The curves represent a plot of the relative phase of the reference electrons as a function of axial distance along the tube. Electrons having negative slope have been decelerated. Electrons having positive slope have been accelerated with respect to a nonaccelerated electron parallel to the axis. The diagram shows how the electrons are nicely grouped at the output cavity gap while the interbunch regions are relatively free of electrons.

This interaction can be viewed another way, as shown in [Figure 6.32](#), which plots the normalized RF beam currents as a function of distance along the tube. The curves show that the fundamental component of the plasma wave has a negative slope at the third gap. This normally would be a poor condition, but because of the drift of the interbunch



**Figure 6.31** Plot of the relative phase of the reference electrons as a function of axial distance in a high-efficiency klystron.

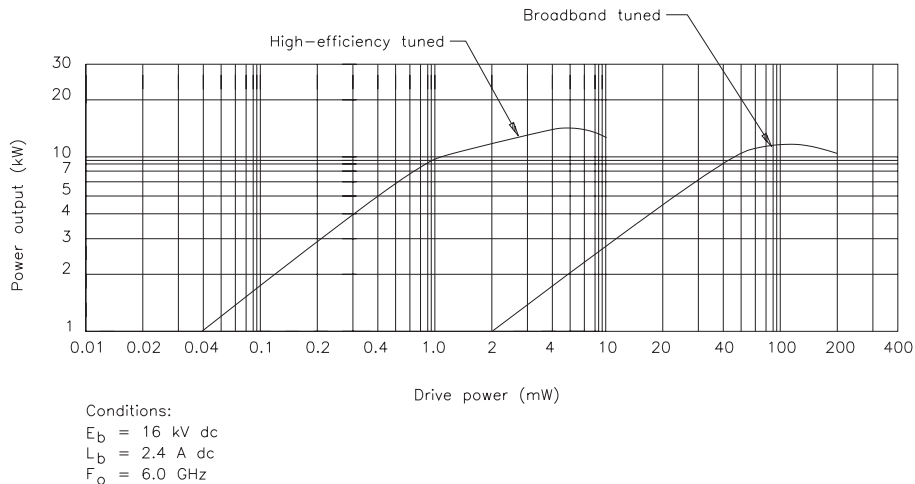


**Figure 6.32** Plot of the normalized RF beam currents as a function of distance along the length of a high-efficiency klystron.

electrons, the fundamental current peaks at nearly 1.8 times the dc beam current. The theoretical limit for perfect bunching in a delta function is 2. The second harmonic of the plasma wave also peaks at the output gap, which adds to the conversion efficiency.

### Types of Devices

Klystrons can be classified according to the following basic parameters:



**Figure 6.33** Typical gain, output power, and drive requirements for a klystron.

- Power operating level. Klystrons are available ranging from a few hundred watts to more than 10 MW.
- Operating frequency. Klystrons typically are used over the frequency range of 300 MHz to 40 GHz.
- Number of cavities. The number of resonant cavities may range from one to five or more. Furthermore, the cavities may be *integral* or *external* to the vacuum envelope of the device.

The klystron is a true linear amplifier from zero signal level up to 2 to 3 dB below saturated output. Figure 6.33 shows a typical transfer characteristic for a klystron. RF modulation is applied to the input drive signal. Amplitude modulation typically is limited to the linear portion of the gain transfer characteristic (class A operation). The result is low efficiency, because the beam power is always on. For applications requiring frequency modulation, the drive power is set for saturated output.

Pulse modulation of the klystron may be obtained by applying a negative rectangular voltage, instead of a dc voltage, to the cathode. The RF drive, set to a saturation value, usually is pulsed on for a slightly shorter time than the beam pulse.

Because of the high power levels typically used at UHF frequencies, device efficiency is a critical parameter. Klystrons usually are rated in terms of *saturated efficiency*, determined by dividing the saturated RF output power by the dc input power.

Saturated efficiency governs the maximum *peak-of-sync efficiency* available when beam-pulsing techniques are employed for UHF-TV service. Peak-of-sync efficiency is the commonly used *figure of merit* (FOM) expression, defined as the peak-of-sync output power divided by the dc input power.

**Table 6.1** Typical Operating Parameters for an Integral-Cavity Klystron for UHF-TV Service (*Courtesy of Varian.*)

| Parameter                    | Typical Value |
|------------------------------|---------------|
| Operating frequency (visual) | 519 MHz       |
| Output power, peak-of-sync   | 64 kW         |
| Drive power, peak-of-sync    | 15 W          |
| Gain, peak-of-sync           | 36 dB         |
| Efficiency, saturated        | 55%           |
| Bandwidth, -1 dB             | 6 MHz         |
| Beam voltage                 | 24.5 kV       |
| Beam current                 | 4.8 A         |
| Body current                 | 10 MA dc      |
| Modulating-anode voltage     | 17 kV dc      |
| Modulating-anode current     | 0.5 mA dc     |
| Focusing current             | 30 A dc       |
| Load VSWR                    | > 1.1:1       |
| Collector temperature        | 130°C         |

Table 6.1 lists typical operating parameters for an integral-cavity klystron.

### 6.3.4 Beam Pulsing

Beam pulsing is a common method of improving the efficiency of a broadband linear klystron amplifier. Depending on the transmitted waveform, efficiency may be boosted by 25 percent or more. This technique typically is used in UHF-TV transmitters to reduce visual klystron beam dissipation during video portions of the transmission. *Sync pulsing*, as the technique is commonly known, is accomplished by changing the operating point of the tube during the synchronizing interval, when peak power is required, and returning it to a linear transfer characteristic during the video portion of the transmission.

This control is accomplished through the application of a voltage to an electrode placed near the cathode of the klystron. Biasing toward cathode potential increases the beam current, and biasing toward ground (collector potential) decreases beam current.

In the composite TV waveform, video information occupies 75 percent of the amplitude, and sync occupies the remaining 25 percent. The *tip of sync* represents the peak power of the transmitted waveform. Black (the *blanking level*) represents 56 percent of the peak power. If the blanking level could be made to represent 100 percent modulation and the sync pulsed in, as in a radar system, efficiency would be increased significantly. Unfortunately, the color-burst signal extends 50 percent into the sync region, and any attempt to completely pulse the sync component would distort the color-burst reference waveform. Sync pulsing is, therefore, limited to 12.5 percent above black to protect color-burst. Two common implementations of beam pulsing can be found:



- Modulating-anode (mod-anode) pulsing
- Annular beam control electrode (ACE) pulsing

The mod-anode system (first discussed in Section 6.3.3) utilizes an additional electrode after the cathode to control beam power. The ACE-type tube operates on a similar principle, but the annular ring is placed close to the cathode so that the ring encloses the electron beam. Because of the physical design, pulsing with the ACE-type gun is accomplished at a much lower voltage than with a mod-anode device. The ACE element, in effect, grid-modulates the beam.

In theory, the amount of beam-current reduction achievable and the resulting efficiency improvement are independent of whether mod-anode or ACE-type pulsing are used. In practice, however, differences are noted. With existing mod-anode pulsers, an efficiency improvement of about 19 percent in beam current over nonpulsed operation may be achieved. A beam reduction of 30 to 35 percent may be achieved through use of an ACE-equipped tube. The effect of ACE voltage on beam current is shown in [Figure 6.34](#) for an external-cavity klystron.

The ACE electrode, positioned in the gun assembly, is driven by a negative-directed narrowband video signal of a few hundred volts peak. The annular ring varies the beam density through a *pinching action* that effectively reduces the cross-sectional area of the stream of electrons emitted by the cathode. The klystron thus operates in a quasi-class-AB condition rather than the normal class A (for linear TV service).

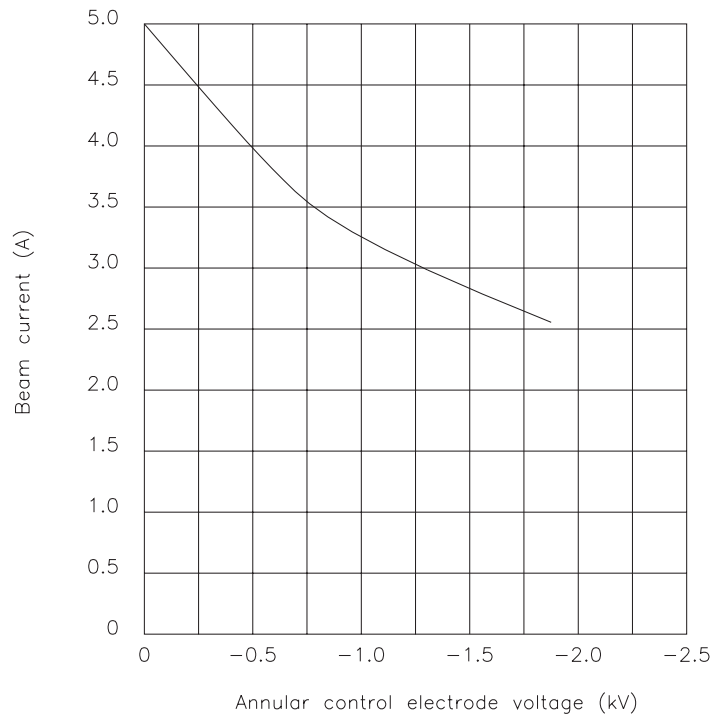
A peak-of-sync FOM for an integral-cavity UHF-TV klystron without ACE or equivalent control is 0.67 to 0.68. Through the use of an ACE-type tube, the FOM may be increased to 0.80. Similar improvements in efficiency can be realized for external-cavity klystrons. A typical switching-type mod-anode pulser is shown in [Figure 6.35](#).

Pulsing is not without its drawbacks, however. The greater the pulsing, the greater the precorrection required from the modulator. Precorrection is needed to compensate for nonlinearities of the klystron transfer characteristic during the video modulation period. Level-dependent RF phase precorrection also may be required. Switching between different klystron characteristics produces phase modulation of the visual carrier. If not corrected, this phase modulation may result in intercarrier “buzz” in the received audio. These and other considerations limit the degree of pulsing that may be achieved on a reliable basis.

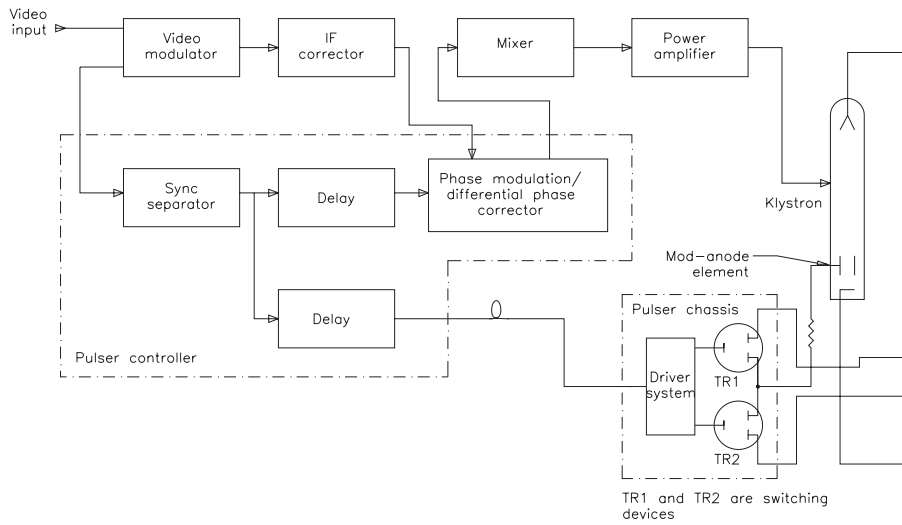
### 6.3.5 Integral vs. External Cavity

In an integral-cavity klystron, the resonant cavities are located within the vacuum envelope of the tube. In an external-cavity klystron, the cavities are located outside the envelope in a mechanical assembly that wraps around the drift tube.

Fundamentally, klystron theory applies equally to integral- and external-cavity tubes. In both cases, a velocity-modulated electron beam interacts with multiple resonant cavities to provide an amplified output signal. The resonant cavity *interaction gap* and drift length requirements for optimum performance—including conversion efficiency—are independent of whether the tuning mechanism is inside or outside the vac-



**Figure 6.34** Klystron beam current as a function of annular control electrode voltage.



**Figure 6.35** Block diagram of a switching mod-anode pulser.

uum envelope. High-efficiency integral- and external-cavity klystrons have been designed to provide maximum conversion performance consistent with signal bandwidth requirements. The saturated conversion efficiency is essentially identical for integral- or external-cavity klystrons with equal numbers of resonant cavities.

### **Number of Cavities**

The relative benefits of integral- vs. external-cavity klystrons can be debated at length. Discussion typically centers on operating efficiency, life expectancy, and replacement device cost. In a comparison of the efficiency of integral- vs. external-cavity klystrons for UHF-TV applications, however, the question really boils down to the number of cavities (four or five) used in the device. Four-cavity external tubes are standard. It is usually not practical to produce high-power five-cavity external tubes for mechanical and electrical (voltage standoff) reasons.

Integral devices permit the addition of a fifth cavity to the design for two primary reasons. First, the device itself is mechanically more robust. The addition of a fifth cavity to an external klystron increases the length and weight of the device. Because of the size of the drift tube in an external device designed for UHF-TV frequencies, the additional weight is difficult to support. Second, because the cavities are enclosed in a vacuum in the integral design, voltage standoff problems are greatly reduced.

The tuning mechanism of an integral-cavity klystron is enclosed in a rigid steel shell. In the external-cavity unit, the tuning mechanism is in air. Within the region of the tuning mechanism, RF fields can reach high levels, especially at the high end of the UHF-TV band. The highest energy field occurs in the area of the last cavity. Because of the high dielectric properties of a vacuum, dielectric breakdown is less of a problem in the integral design, which places the tuning mechanism within a vacuum envelope. This situation is of particular concern at the high end of the UHF band, where the spacing of tuning elements is closer.

Four-cavity integral-type klystrons are manufactured, but for power outputs of 30 kW or less. The 60 kW integral klystron, typically used for UHF-TV broadcasting, is produced as a five-cavity design.

The physics of the integral- and external-cavity klystrons are essentially the same. In a comparison of integral and external units of like design—that is, with the same number of cavities—performance should be identical. The two units follow the same laws of physics and use basically the same components up to the beam stick. It is when manufacturers take advantage of the relative merits of each design that differences in performance are realized.

### **Efficiency**

For the sake of comparison, the data presented in this section will assume:

- The power level is 60 kW
- All integral-cavity devices utilize five cavities
- All external-cavity devices utilize four cavities

The five-cavity integral *S-tuned* klystron is inherently at least 20 percent more efficient than a four-cavity tube. (*S-tuning* refers to the method of stagger tuning the cavities.) The five-cavity klystron generally is specified by the manufacturer for a minimum efficiency of 52 percent (saturated efficiency). Typical efficiency is 55 percent. Four-cavity devices are characteristically specified at 42 percent minimum and 45 percent typical.

This efficiency advantage is possible because the fifth cavity of the integral design permits tuning patterns that allow maximum transfer of RF energy while maintaining adequate bandpass response. Tighter bunching of electrons in the beam stick, a function of the number of cavities, also contributes to the higher efficiency operation. In actuality, the fifth cavity allows design engineers to trade gain for efficiency. Still, the five-cavity tube has significantly more gain than the four-cavity device. The five-cavity unit, therefore, requires less drive, which simplifies the driving circuit. A five-cavity klystron requires approximately 25 W of drive power, while a four-cavity tube needs as much as 90 W for the same power output.

Under pulsed operation, approximately the same reduction in beam current is realized with both integral- and external-cavity klystrons. In a comparison of peak-of-sync FOM, the efficiency differences will track. There is, fundamentally, no reason that one type of klystron should pulse differently than the other.

### **Performance Tradeoffs**

It is the designer's choice whether to build a transmitter with the klystron cavities located inside or outside the vacuum envelope. There are benefits and drawbacks to each approach.

When the cavity resonators are a part of the tube, the device becomes more complicated and more expensive. However, the power generating system is all together in one package, which simplifies installation significantly.

When the resonator is separate from the tube, as in an external-cavity device, it can be made with more *compliance* (greater room for adjustment). Consequently, a single device may be used over a wider range of operating frequencies. In terms of UHF-TV, a single external-cavity device may be tuned for operation over the entire UHF-TV band. This feature is not possible if the resonant cavities are built into the device. To cover the entire UHF-TV band, three integral-cavity tubes are required. The operational divisions are:

- Channels 14 to 29 (470 to 566 MHz)
- Channels 30 to 51 (566 to 698 MHz)
- Channels 52 to 69 (698 to 746 MHz)

This practical limitation to integral-cavity klystron construction may be a drawback for some facilities. For example, it is not uncommon for group operations to share one or more spare klystrons. If the facilities have operating frequencies outside the limits of a single integral device, it may be necessary to purchase more than one spare. Also,

when the cavities are external, the resonators are in air and can be accessed to permit fine adjustments of the tuning stages for peak efficiency.

The advantages of tube changing are significant with an integral device. Typical tube change time for an integral klystron is 1 hour, as opposed to 4 to 6 hours for an external device. The level of experience of the technician is also more critical when an external-type device is being changed. Tuning procedures must be carefully followed by maintenance personnel to avoid premature device failure.

### 6.3.6 MSDC Klystron

Developmental work on the multistage depressed collector (MSDC) klystron began in the mid-1980s. The project<sup>1</sup> produced a working tube capable of efficiency in UHF service that had been impossible with previous klystron-based technology.

The MSDC device may be used in a number of varied applications. NASA originally became involved in the project as a way to improve the efficiency of satellite transmitters. With limited power available onboard a space vehicle, efficient operation is critically important. Such transmitters traditionally operate in a linear, inefficient mode. UHF-TV broadcasters were interested in the MSDC because it promised to reduce the huge operating costs associated with high-power operation.

Experimentation with depressed collector klystrons dates back to at least the early 1960s. Early products offered a moderate improvement in efficiency, but at the price of greater mechanical and electrical complexity. The MSDC design, although mechanically complex, offers a significant gain in efficiency.

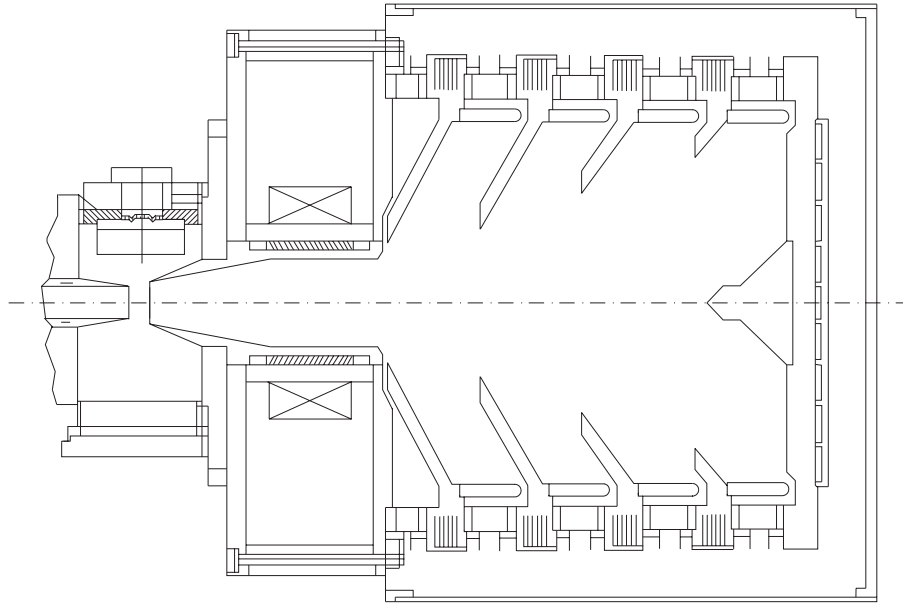
#### Theory of Operation

MSDC tubes have been built around both integral-cavity and external-cavity klystrons. The devices are essentially identical to a standard klystron, except for the collector assembly. Mathematical models provided researchers with detailed information on the interactions of electrons in the collector region. Computer modeling also provided the basis for optimization of a *beam-reconditioning* scheme incorporated into the device. Beam reconditioning is achieved by including a *transition region* between the RF interaction circuit and the collector under the influence of a magnetic field. It is interesting to note that the mathematical models made for the MSDC project translated well into practice when the actual device was constructed.

From the electrical standpoint, the more stages of a multistage depressed collector klystron, the better. The tradeoff, predictably, is increased complexity and, therefore, increased cost for the product. There is also a point of diminishing returns that is reached as additional stages are added to the depressed collector system. A four-stage device was chosen for TV service because of these factors. As more stages are added (beyond four), the resulting improvement in efficiency is proportionally smaller.

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<sup>1</sup> A joint effort of the National Aeronautics and Space Administration (NASA), several UHF-TV transmitter manufacturers, Varian Associates, and other concerns.



**Figure 6.36** Mechanical design of the multistage depressed collector assembly. Note the “V” shape of the 4-element system.

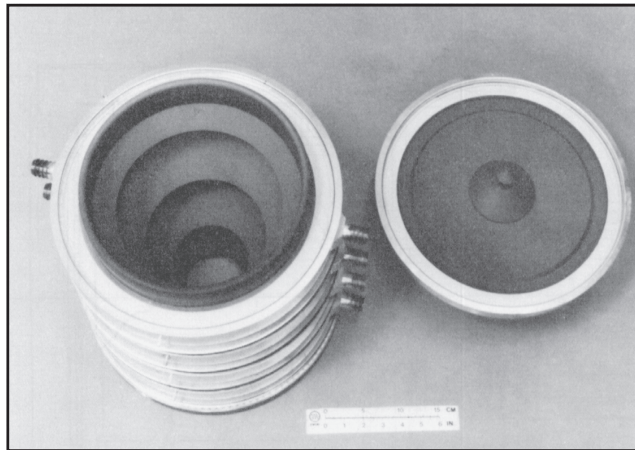
Figure 6.36 shows the mechanical configuration of the four-stage MSDC klystron. Note the “V” shape that was found, through computer modeling, to provide the best *capture* performance, minimizing electron feedback. A partially assembled collector assembly is shown in Figure 6.37.

Because the MSDC device is identical to a conventional klystron except for the collector, efficiency improvement techniques used for klystrons can be incorporated into the MSDC. ACE-type pulsing commonly is used to improve efficiency in TV applications. Figure 6.38 illustrates the effects of ACE voltage on beam current.

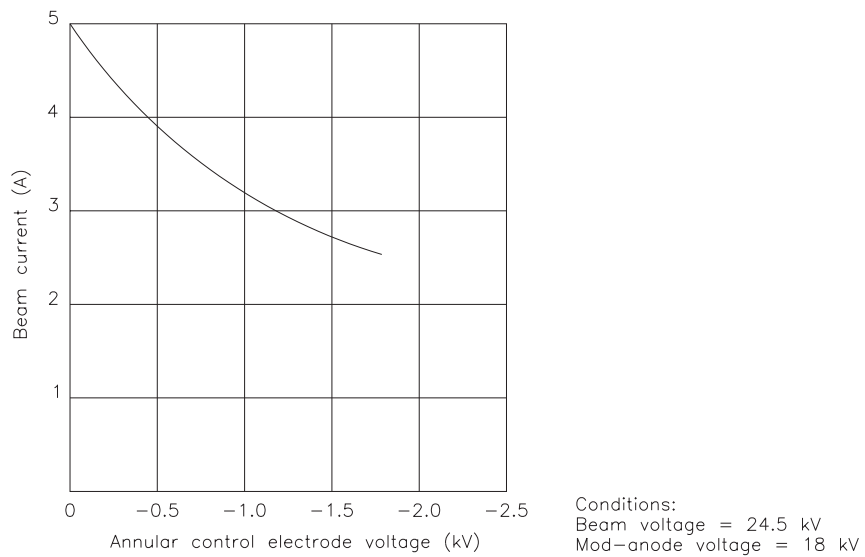
### Electron Trajectories

The dispersion of electrons in the multistage collector is the key element in recovering power from the beam and returning it to the power supply. This is the mechanism that permits greater operating efficiency from the MSDC device.

Figure 6.39 illustrates the dispersion of electrons in the collector region during a carrier-only operating mode. Note that there is little dispersion of electrons between stages of the MSDC. Most are attracted to electrode 4, the element at the lowest potential (6.125 kV), referenced to the cathode.

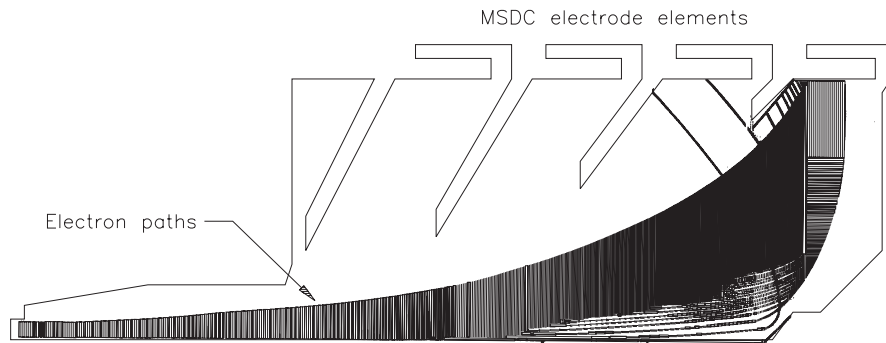


**Figure 6.37** A partially assembled MSDC collector. (Courtesy of Varian.)

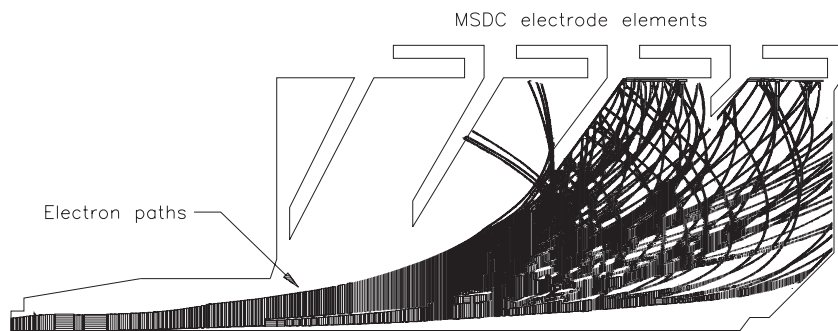


**Figure 6.38** Beam current as a function of annular control electrode voltage for an MSDC klystron.

Figure 6.40 shows collector electron trajectories at 25 percent saturation. The electrons exhibit predictable dispersion characteristics during the application of modulation, which varies the velocity of the electrons. This waveform is a reasonable approximation of *average modulation* for a typical video image.



**Figure 6.39** Collector electron trajectories for the carrier-only condition. Note that nearly all electrons travel to the last electrode (4), producing electrode current  $I_4$ .



**Figure 6.40** Collector trajectories at 25 percent saturation. With the application of modulation, the electrons begin to sort themselves out.

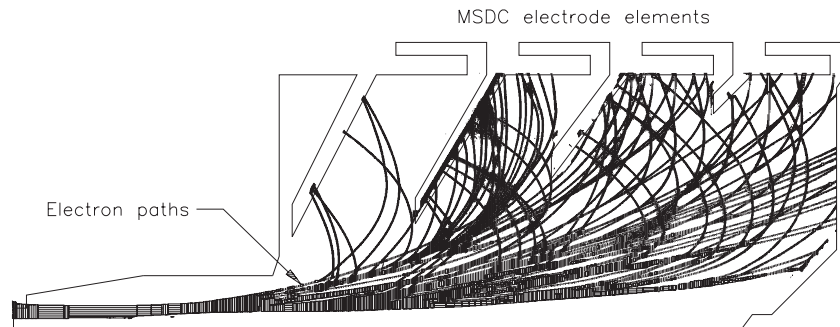
Figure 6.41 shows electron trajectories at 50 percent saturation, approximately the *blanking* level. Note the increased number of electrons attracted to electrodes 2 and 3, the higher-potential electrodes (referenced to the cathode).

Figure 6.42 illustrates electron dispersion at 90 percent saturation, approximately the level of sync in a video waveform. As the modulation level is increased, more electrons are attracted to the higher-voltage electrodes. The dramatic increase in electron capture by electrode 1, the highest-potential element of the device (at a voltage of 24.5 kV, referenced to the cathode), can be observed.

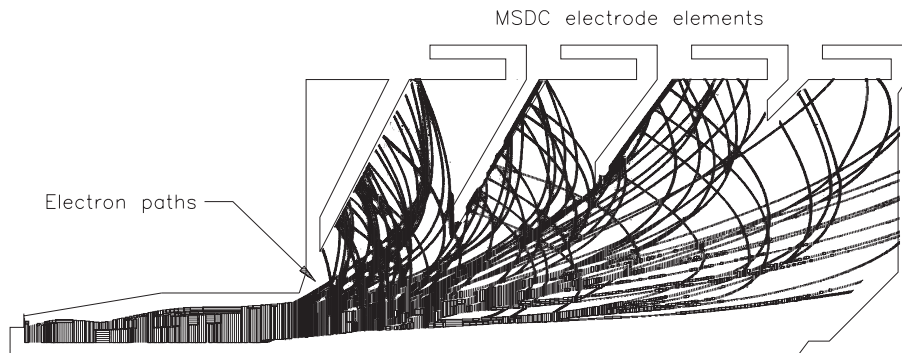
The electrons, thus, sort themselves out in a predictable manner. Notice the arc that is present on many electron traces. The electrons penetrate the electrostatic field of the collector, then are pulled back to their respective potentials.

A savings in power is realized because the electrostatic forces set up in the MSDC device slow down the electrons before they contact the copper collector electrode. The heat that would be produced in the collector is, instead, returned to the power supply in





**Figure 6.41** Collector electron trajectories at 50 percent saturation, approximately the blanking level. The last three electrodes (2, 3, and 4) share electrons in a predictable manner, producing currents  $I_2$ ,  $I_3$ , and  $I_4$ .

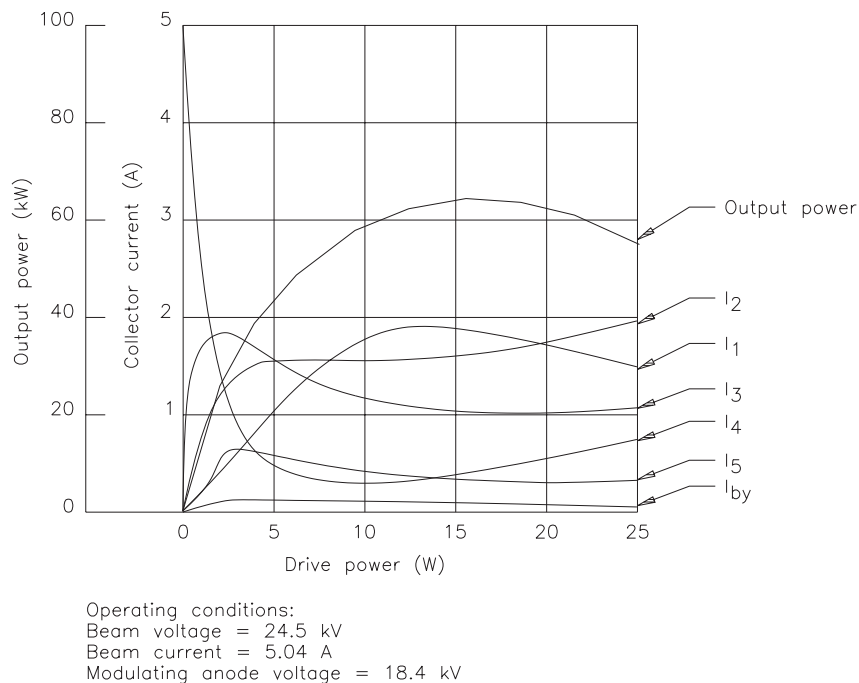


**Figure 6.42** Collector trajectories at 90 percent saturation, the sync level. Note the significant increase in the number of electrons attracted to the first electrode, producing  $I_1$ .

the form of electric energy. In theory, peak efficiency would occur if the electrons were slowed down to zero velocity. In practice, however, that is not possible.

Figure 6.43 shows the distribution of collector current as a function of drive power. With no RF drive, essentially all current goes to electrode 4, but as drive is increased,  $I_4$  drops rapidly as collector current is distributed among the other elements. Note that the current to electrode 5 (cathode potential) peaks at about 10 percent of beam current. This suggests that the *secondary yield* of the collector surfaces is within acceptable limits.

Inserted between the klystron and the collector assembly is a refocusing electromagnet that controls the electron beam as it enters the collector region.



**Figure 6.43** The distribution of electrode current as a function of drive power. Note the significant drop in  $I_4$  as drive power is increased.  $I_5$  is the electrode at cathode potential.

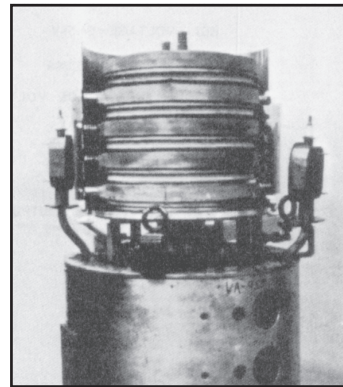
### Mechanical Construction

The completed MSDC assembly is shown in [Figure 6.44](#) with the collector shield partially removed to allow visibility of the collector elements. The collector of the four-stage MSDC design actually is composed of five elements mounted between ceramic rings for electrical insulation. The fifth electrode is at cathode potential.

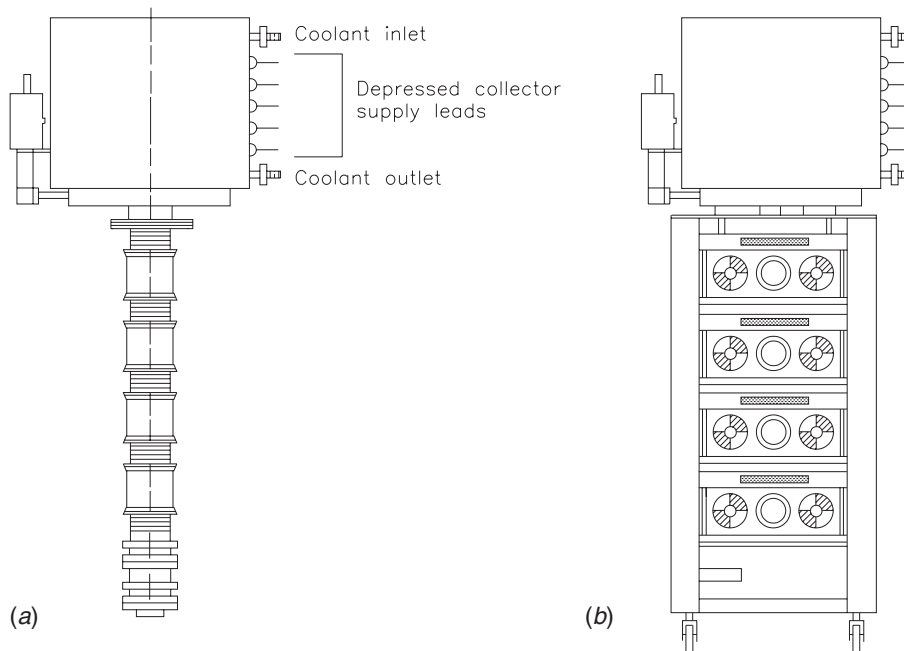
Cooling for the MSDC is, not surprisingly, more complicated than for a conventional klystron. The tradeoff, however, is that there is less heat to remove because of the higher efficiency of the device. Water cooling is provided on each electrode of the MSDC tube.

[Figure 6.45](#) illustrates the overall mechanical design of an external-cavity version of the MSDC tube, including placement of the device in its cavity bay.

Although the MSDC has not been in service for a sufficient length of time to completely characterize the product life expectancy, researchers believe that the MSDC design will have little, if any, effect on the lifetime of the klystron. The electron beam is essentially unchanged. The tube is identical to a conventional integral- or external-cavity klystron except in collector assembly.



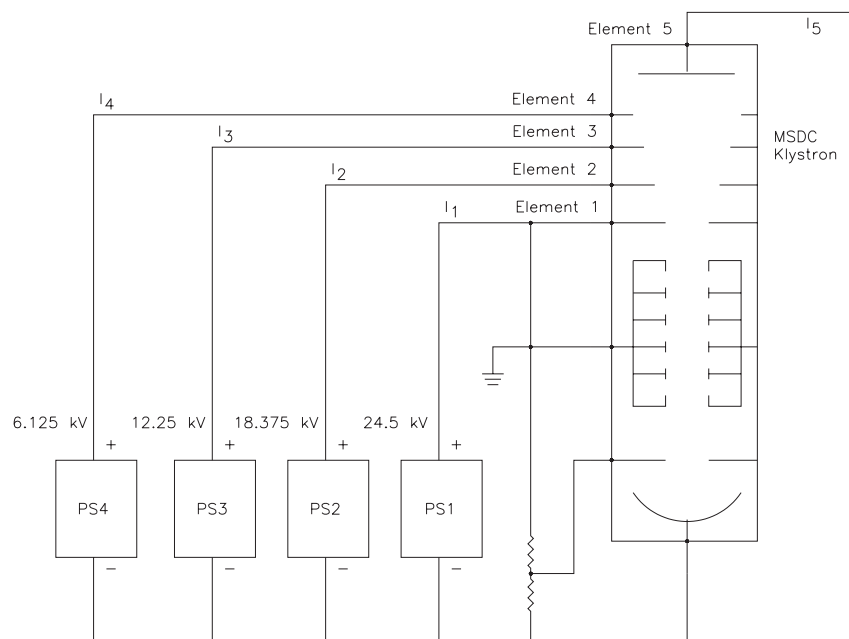
**Figure 6.44** The MSDC collector assembly with the protective shield partially removed. (Courtesy of Varian.)



**Figure 6.45** Mechanical construction of an external-cavity MSDC tube: (a) device, (b) device in cavity assembly.

### MSDC Power Supply

Design criteria for the collector power supply system provide a mixed bag of requirements. The critical parameter is the degree of regulation between the cathode and anode. The relative differences between the elements of the collector are not, in most applications, significant. Consequently, the bulk of the power supplied to the tube does not need to be well regulated. This is in contrast with conventional klystron operation,



**Figure 6.46** Parallel configuration of the MSDC power supply. Each supply section has an output voltage that is an integral multiple of 6.125 kV.

in which the entire beam power supply must be regulated. This factor effectively decreases the amount of power that must be regulated to 1 to 2 percent of the dc input, offsetting to some extent the additional cost involved in constructing multiple supplies to facilitate the 4-stage MSDC design. Two approaches can be taken to collector power supply design:

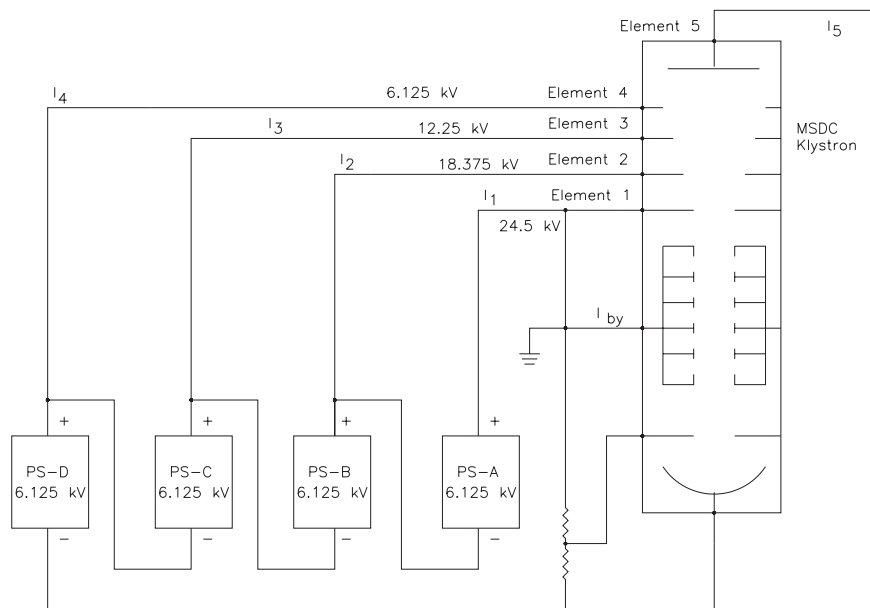
- Parallel arrangement, shown in [Figure 6.46](#)
- Series arrangement, shown in [Figure 6.47](#)

Note that, in both cases, the collector electrodes are stepped at a 6.125 kV potential difference for each element.

### Device Performance

The efficiency improvement of the MSDC klystron over the conventional klystron is impressive. For TV applications, the MSDC—in pulsed operation—is more than twice as efficient as a conventional klystron.

The bandpass performance of the device is another critical parameter. [Figure 6.48](#) charts power output as a function of frequency and RF drive at full power. (Drive power is charted from 0.5 to 16 W.) [Figure 6.49](#) charts power output as a function of frequency



**Figure 6.47** Series configuration of the MSDC power supply, which uses four identical 6.125 kV power supplies connected in series to achieve the needed voltages.

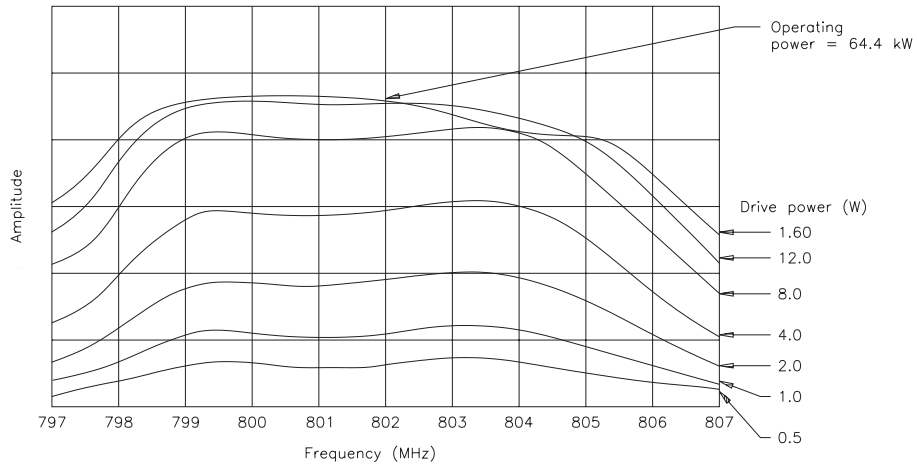
and RF drive with the tube in a beam-pulsing mode. (Drive power is charted from 0.5 to 32 W.) Note that the traces provide good linearity over a 6 MHz bandwidth. Gain, as a function of frequency and power, is essentially constant and undisturbed.

Table 6.2 lists typical operating parameters for an external-cavity MSDC device.

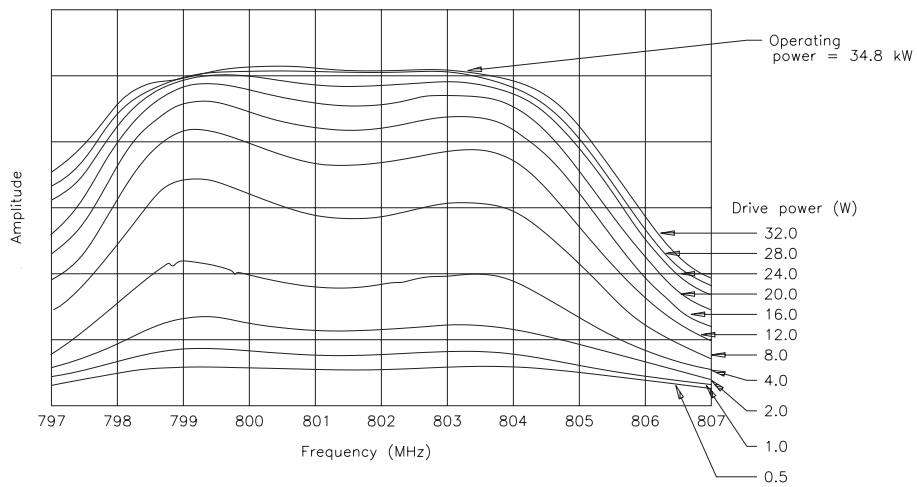
### Applying the MSDC Klystron

A block diagram of a typical system is shown in Figure 6.50. The 60 kW TV transmitter incorporates two external-cavity MSDC klystrons, one for the visual and another for the aural. Design of the transmitter is basically identical to a non-MSDC system, with the exception of the power supply and cooling system. The efficiency available from the MSDC makes further device improvements subject to the law of diminishing returns, as mentioned previously. Support equipment begins to consume an increasingly large share of the power budget as the output device efficiency is improved. Tuning of the MSDC klystron is the same as for a conventional klystron, and the same magnetic circuit is typically used.

The power supply arrangement for the example MSDC system is shown in Figure 6.51. A series beam supply was chosen for technical and economic reasons. Although the current to each collector varies widely with instantaneous output level, the total current stays within narrow limits. Using a single transformer for all supplies, therefore, minimizes the size of the iron core required. A 12-pulse rectifier bank provides low rip-



**Figure 6.48** Device bandwidth as a function of frequency and drive power. Beam voltage is 24.5 kV, and beam current is 5.04 A for an output power of 64 kW. These traces represent the full-power test of the MSDC device.



**Figure 6.49** Device bandwidth in the beam-pulsing mode as a function of frequency and drive power. Beam voltage is 24.5 kV, and beam current is 3.56 A with an output power of 34.8 kW.

**Table 6.2** Typical Operating Parameters for an External-Cavity MSDC Klystron for UHF-TV service (Courtesy of Varian.)

| Parameter                    | Typical Value    |
|------------------------------|------------------|
| Operating frequency (visual) | 519 MHz          |
| Output power, peak-of-sync   | 64 kW            |
| Drive power, peak-of-sync    | 20 W             |
| Gain, peak-of-sync           | 35 dB            |
| Figure of merit              | 1.3 <sup>1</sup> |
| Bandwidth, -1 dB             | 6 MHz            |
| Beam voltage                 | 24.5 kV          |
| Beam current                 | 5.3 A            |
| Body current                 | 50 mA dc         |
| Modulating-anode voltage     | 19.5 kV dc       |
| Modulating-anode current     | 0.5 mA dc        |
| Focusing current             | 11 A dc          |
| Ion pump voltage             | 3.2 kV dc        |
| Load VSWR                    | > 1.1:1          |
| Refocusing coil current      | 7 A dc           |
| Refocusing coil voltage      | 10 V dc          |

<sup>1</sup> Figure of merit is equal to the quotient of peak-of-sync output power and the average dc beam input power.

ple and reduces the need for additional filtering. The size and complexity of the rectifier stack are increased little beyond a normal beam supply because the total potential of the four supplies is similar to that of a normal klystron transmitter (24.5 to 27.5 kV).

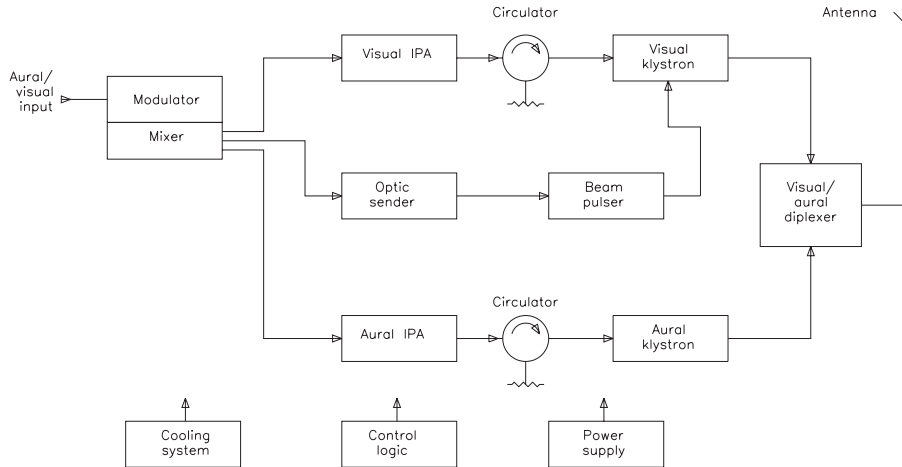
The collector stages of the MSDC device are water-cooled by a single water path that loops through each electrode element. Because high voltage is present on the individual elements, purity of the water is critical to proper operation. A two-stage system is used with a water-to-water plate heat exchanger separating the primary and secondary systems.

## 6.4 Klystrode/Inductive Output Tube (IOT)

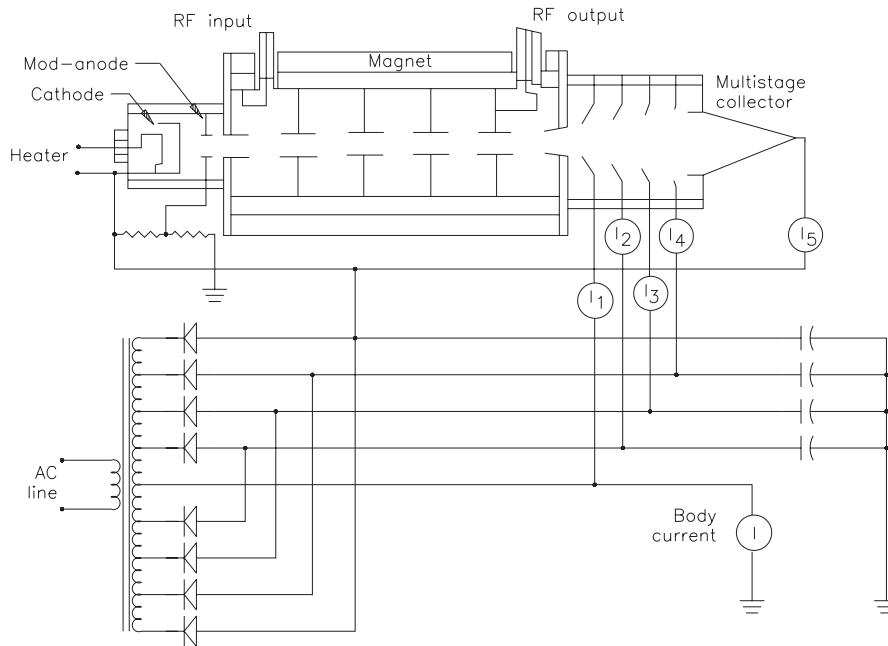
The Klystrode tube is the result of a development program started in 1980<sup>2</sup> with UHF-TV in mind as a primary application. The basic concept of the Klystrode dates back to the late 1930s,<sup>3</sup> but it was not until the early 1980s that serious engineering effort was put into the tube to make it a viable product for high-power UHF service. The fundamental advantage of the Klystrode, also known as the *inductive output tube*

<sup>2</sup> Varian/Eimac

<sup>3</sup> Andrew Haeff, 1938



**Figure 6.50** Simplified block diagram of a 60 kW (TVT) MSDC transmitter. The aural klystron may utilize a conventional or MSDC tube at the discretion of the user.



**Figure 6.51** Simplified schematic diagram of the power supply for an MSDC klystron transmitter. A single high-voltage transformer with multiple taps is used to provide the needed collector voltage potentials.



(IOT), is its ability to operate class B. The result is higher efficiency when compared with a conventional klystron.

### 6.4.1 Theory of Operation

As its name implies, the Klystrode tube is a hybrid between a klystron and a tetrode. The high reliability and power-handling capability of the klystron is due, in part, to the fact that electron beam dissipation takes place in the collector electrode, quite separate from the RF circuitry. The electron dissipation in a tetrode is at the anode and the screen grid, both of which are an inherent part of the RF circuit and, therefore, must be physically small at UHF frequencies. The tetrode, however, has the advantage that modulation is produced directly at the cathode by a grid so that a long drift space is not required to produce density modulation. The Klystrode/IOT has a similar advantage over the klystron—high efficiency in a small package [4]. The Klystrode tube is a registered trademark of Varian. The IOT is the generic description for the device, and it will be used in this discussion.

The IOT is shown schematically in [Figure 6.52](#). The electron beam is formed at the cathode, density-modulated with the input RF signals by a grid, then accelerated through the anode aperture. In its bunched form, the beam drifts through a field-free region, then interacts with the RF field in the output cavity. Power is extracted from the beam in the same way as in a klystron. The input circuit resembles that of a typical UHF power grid tube. The output circuit and collector resemble those in a klystron.

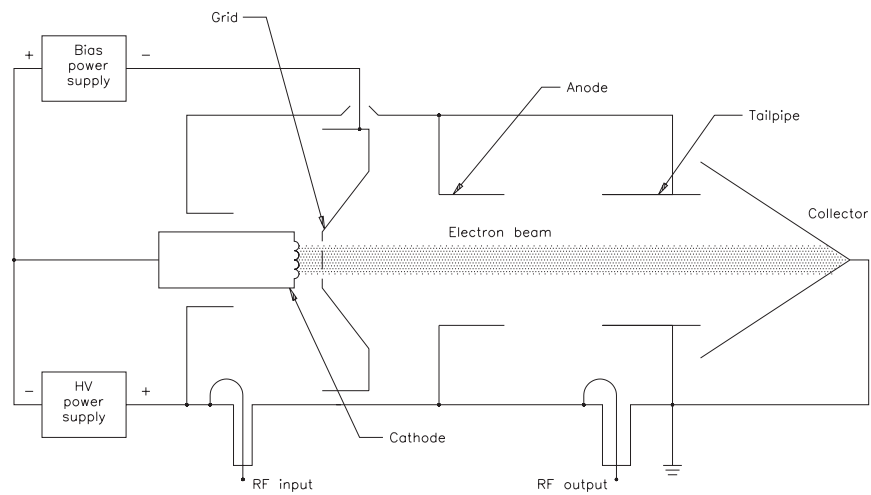
A production version of a 60 kW device is shown in [Figure 6.53](#). Double-tuned cavities are used to obtain the required operating bandwidth. The load is coupled at the second cavity, as shown in [Figure 6.54](#). This arrangement has proved to be an attractive way to couple power out of the device because no coupling loop or probe is required in the primary cavity, which can be a problem at the high end of the UHF band.

Because the IOT provides both beam power variation during sync pulses (as in a pulsed klystron) and variation of beam power over the active modulating waveform, it is capable of high efficiency. The device provides full-time beam modulation as a result of its inherent structure and class B operation.

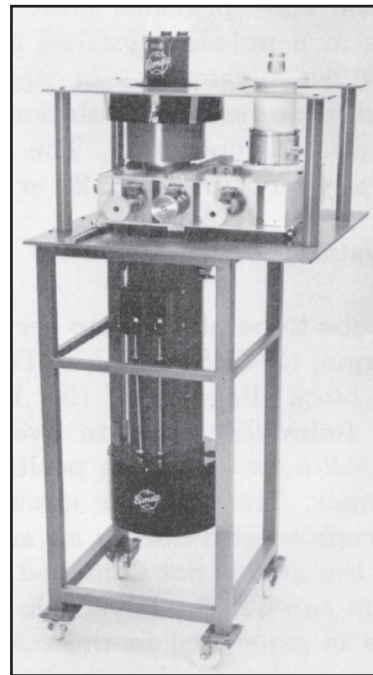
### 6.4.2 Electron Gun

Many design elements from the klystron have been borrowed for use in the IOT [4]. A barium aluminate cathode is used for the gun, taken from a conventional klystron together with its heater structure. The methods used to support the cathode, heater, and necessary heat shields in the klystron gun have been retained for use in the IOT. [Figure 6.55](#) shows the construction of the IOT gun and output cavity.

In the IOT, the RF input voltage is applied between the cathode and a grid that allows extra electrons to be drawn from the cathode into a low-quiescent-current electron beam according to the instantaneous RF voltage appearing between the grid and cathode. The resulting density-modulated beam is then passed into the klystron-like RF output interaction region of the tube.

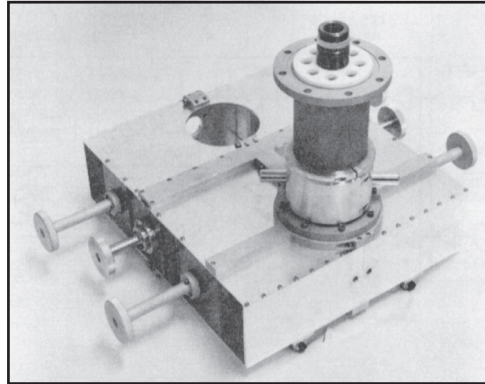


**Figure 6.52** Simplified schematic diagram of the Klystron tube.



**Figure 6.53** A 60 kW Klystron tube mounted in its support stand with the output cavity attached. (Courtesy of Varian.)

The grid is clamped in place in front of the cathode, supported on a metal cylinder, and isolated from the cathode by a ceramic insulator. A second ceramic insulator supports the complete gridded electron gun at the correct distance from the grounded an-



**Figure 6.54** A close-up view of the double-tuned output cavity of a 60 kW Klystron tube. (Courtesy of Varian.)

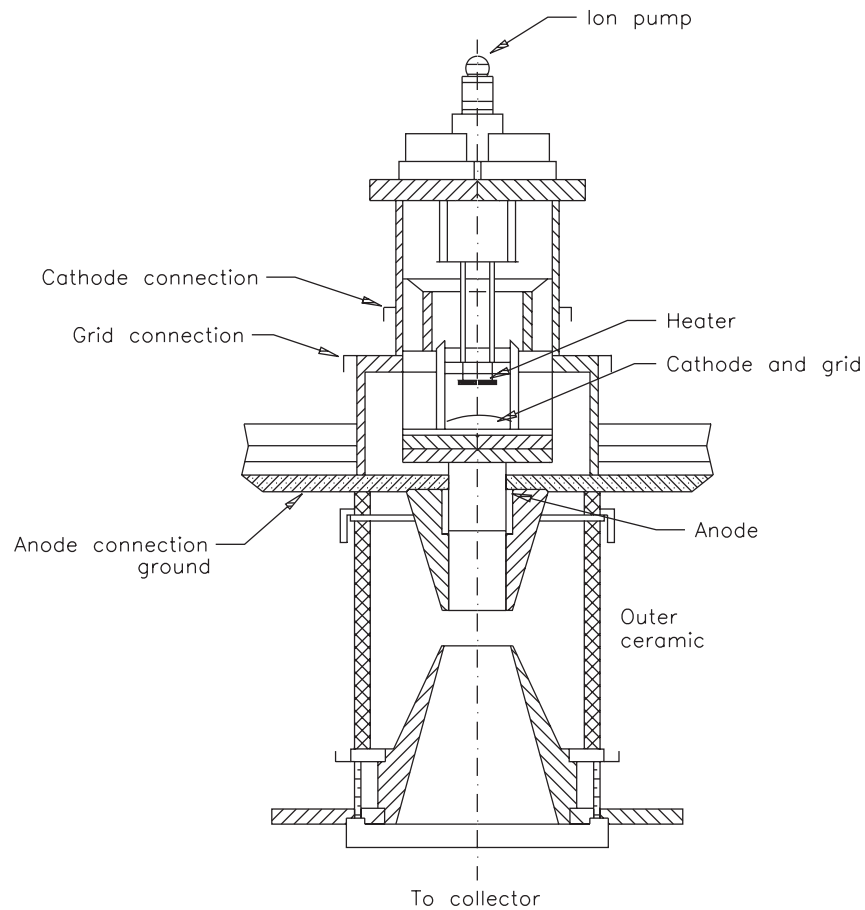
ode. This ceramic insulator completes the vacuum envelope and holds off the full beam voltage of approximately 30 kV. The IOT gun operates at cathode-to-anode voltages approximately 50 percent higher than those of conventional klystron guns. Stray capacitance in the grid support structure has been minimized to reduce losses.

The grid-to-cathode space of the electron gun forms the end of a long and complex RF transmission line from the RF input connector of the input cavity system. This design has a significant effect upon the final frequency range of the IOT input cavity. Because the grid-to-cathode distance is crucial to the physics of the device, the grid requires a rigid support structure to maintain proper spacing at high operating temperatures.

### 6.4.3 Grid Structure

A pyrolytic graphite grid is used in the IOT because of its strength and its ability to maintain desired specifications at elevated temperatures [4]. Pyrolytic graphite has a unique advantage over other common grid materials in that its strength increases as the temperature climbs to 2500°C and above, whereas the strength of pure metals universally decreases as the temperature increases. This allows the designer to produce a thin grid, with fine grid wires that may be accurately positioned and will retain their position and shape when raised to operating temperatures of approximately 1000°C.

During production of the grid, a hydrocarbon, typically methane, is fed into a low-pressure chamber containing a graphite rod of the correct form to produce the required graphite shell. A shell typically consists of a graphite cylinder with a closed, shaped end. The cold gas is passed into a hot zone in the reactor, which is heated by an RF eddy current system from outside the vessel. An ordered carbon structure, as opposed to an amorphous structure, is required. To provide the needed processing, the temperature of the reactor is set to approximately 2000°C at a pressure of 10 torr. The graphite shells produced in this way have a layered structure with anisotropic properties and are physically durable.

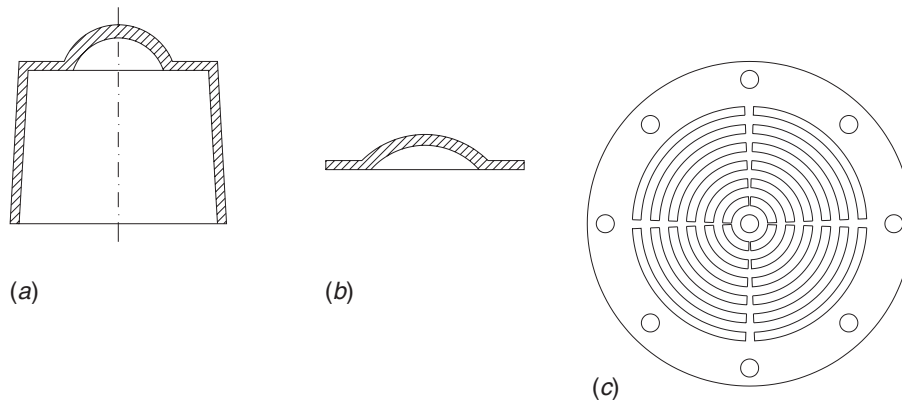


**Figure 6.55** Overall structure of the IOT gun and output cavity. (After [4].)

The shells are then machined to the desired shape and size, and holes are cut into the resulting grid back using a laser under computer control. The process of producing a pyrolytic graphite grid is illustrated in [Figure 6.56](#).

#### 6.4.4 Input Cavity

Although similar, the Klystron and the IOT are not identical. There are both subtle and significant differences in each design. The greatest departure can be seen in the configuration of the input cavity [4]. The design of the IOT is shown in [Figure 6.57](#). A cylindrical resonant cavity containing an annular sliding tuning door is used. The cavity is folded at the IOT electron gun end to make contact with the tube via an RF choke structure. Because both the cathode and grid operate at beam potential (30 kV), it is necessary to maintain the body of the cavity and its tuning mechanism at ground



**Figure 6.56** Pyrolytic graphite grid: (a) shell, (b) grid blank, (c) grid cut.

potential by using RF chokes to prevent leakage of RF energy, while holding off the full beam voltage.

At a given point on the grid connection within the RF choke, an insulated high-voltage cable is attached and exits so that the  $-30$  kV dc can be supplied to the grid. This cable is screened and fitted with RF chokes to prevent UHF energy from passing into the beam power supply. RF input energy is fed via a coaxial cable to the input cavity, which is excited by means of a loop antenna carried by the annular tuning door.

Cooling air for the IOT electron gun and grid connection is fed through an insulated air pipe down the inside of the input cavity.

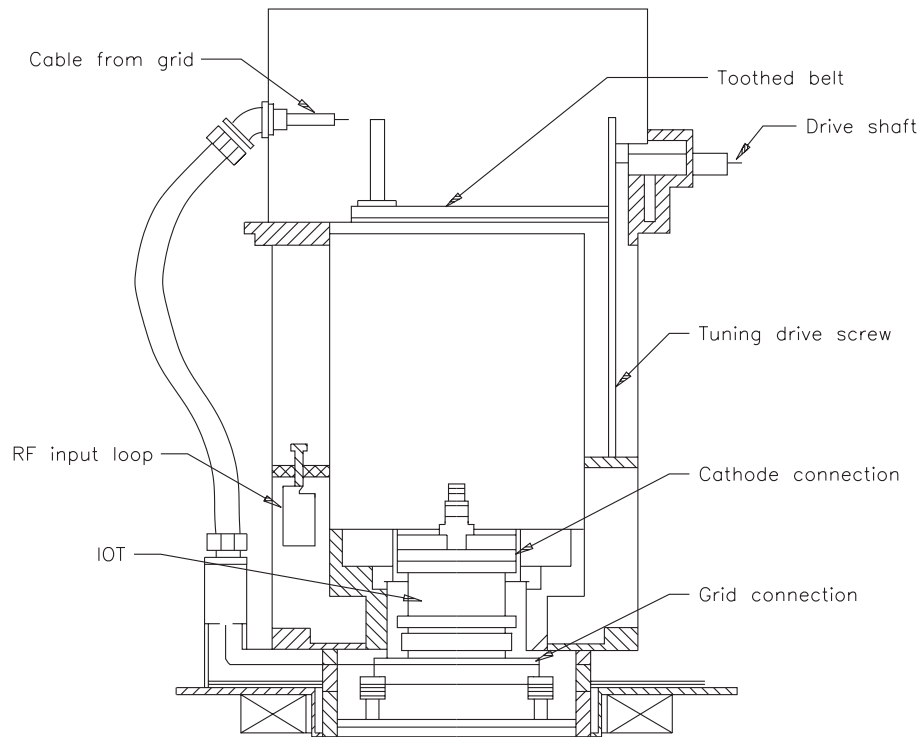
The tuning door of the cavity is driven by three two-stage tuning screws coupled to the outside via a rubber-toothed belt and bevel-gear drive. A mechanical turns-counter is provided to relate cavity door position with operating frequency.

#### 6.4.5 Output Cavity

The primary output cavity is clamped around the output ceramic of the IOT, as on a conventional klystron [4]. The output cavity, shown in Figure 6.58, contains an RF coupling loop that may be rotated about a horizontal axis to adjust the degree of coupling through a short transmission line section into a secondary cavity via a door-knob-type antenna. The secondary cavity contains a dome structure adjusted in size so that the cavity can be made to cover the required frequency band. An output coupler, of standard klystron design incorporating a loop antenna, connects the secondary cavity of the RF output feeder system via a standard output interface. This design provides for instantaneous bandwidths of 8 MHz or greater.

Because RF voltages on the order of the IOT beam voltage can be expected in the output system, RF arc detectors are fitted into both cavities.

Cooling of the output cavities is accomplished by means of filtered forced air. Air enters the primary cavity, passes over the output ceramic and coupling loop, then exits



**Figure 6.57** IOT input cavity. (After [4].)

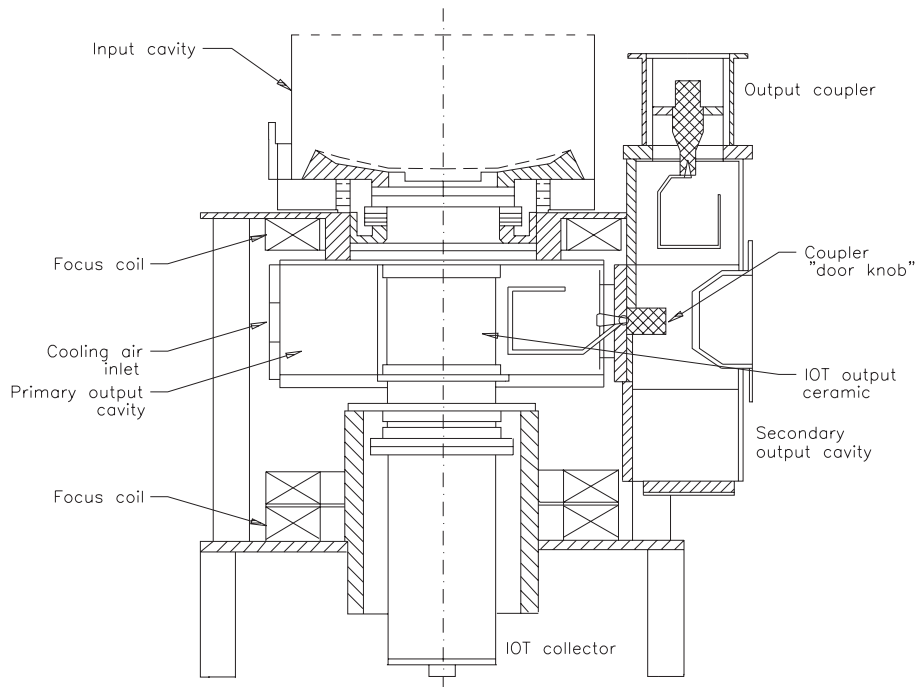
via holes in the coupling hub assembly into the secondary cavity. After cooling the secondary cavity, some of the air exits via the contact fingers on the tuning doors, while a small portion traverses the output loop and coupler, exiting at a stub-pipe fitting for that purpose.

Typical operating parameters for the IOT are shown in [Table 6.3](#).

#### 6.4.6 Application Considerations

An active crowbar circuit is included in most applications of the Klystrode/IOT to protect the pyrolytic graphite grid in the event of an arc condition inside the tube [4]. The crowbar provides the added benefit of reducing the amount of gas generated in the tube during an arc. A block diagram of a typical crowbar is shown in [Figure 6.59](#). The response time of the crowbar is typically less than 10  $\mu\text{s}$ . The peak current permissible through the discharge tube may be 3000 A or greater.

Because of the IOT's class B operation, the response of the power supply to a varying load is an important design parameter. If a standard klystron beam supply were used in an IOT-equipped RF generator, performance under varying modulation levels could

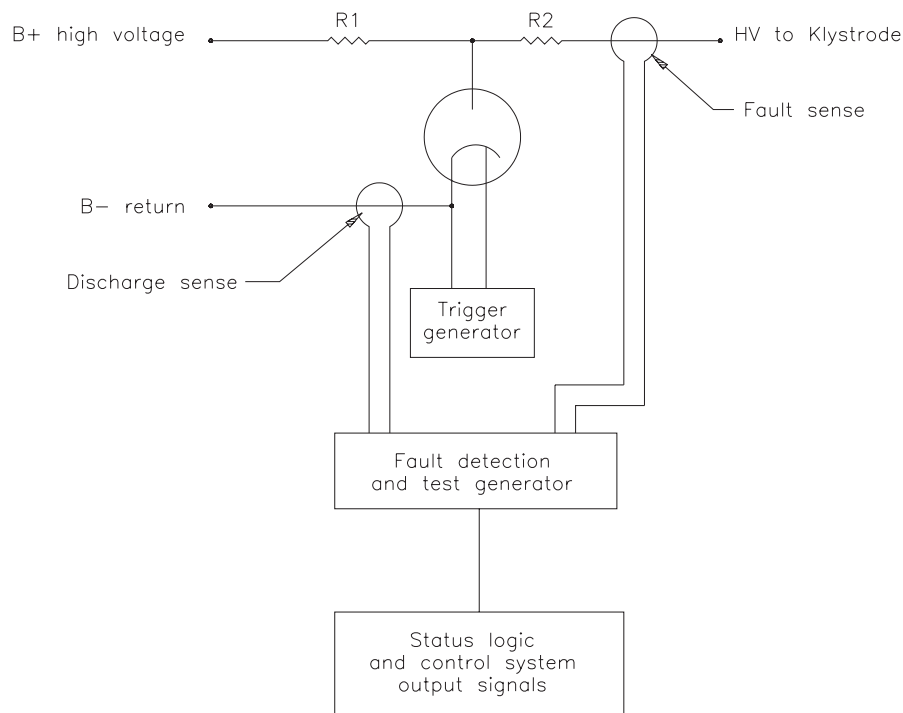


**Figure 6.58** IOT output cavity. (After [4].)

**Table 6.3** Typical Operating Parameters of the IOT in TV Service

| Parameter         | Typical Value |
|-------------------|---------------|
| Beam voltage      | 28 kV         |
| Mean beam current | 1.15 A        |
| Peak beam current | 2.50 A        |
| Grid bias         | -72 V         |
| Grid current      | 1 mA          |
| Body current      | 6 mA          |
| Input power       | 399 W         |
| Output power      | 40.3 kW       |

be unacceptable. Consider the application of a *bounce* (black-to-white) signal to a TV transmitter. Beam current for a typical IOT 60 kW transmitter would change from approximately 400 mA to 2 A. The effect with a conventional klystron supply would be ringing of about 20 percent on the beam voltage. The IOT power supply, therefore, must be designed for tight transient regulation.



**Figure 6.59** Simplified block diagram of the crowbar circuit designed into the Klystrode SK-series (Comark) transmitters. The circuit is intended to protect the tube from potentially damaging fault currents.

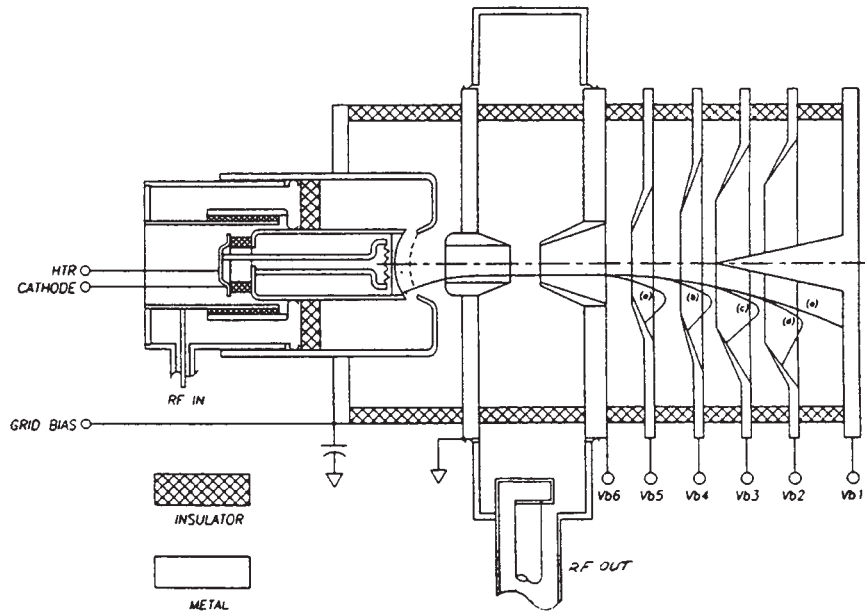
The IOT does not have the same hard saturation characteristic as a klystron. The IOT's high-power transfer curve flattens more slowly than a klystron's and continues to increase with increasing drive power, requiring a different approach to linearity correction.

#### 6.4.7 Continuing Research Efforts

Several variations on the basic Klystrode/IOT theme have been developed, including air-cooled devices operating at 30 kW and above. Air cooling is practical at these power levels because of the improved efficiency that class B operation provides.

Research also is being conducted to extend the operating power of the IOT to 500 kW or more. Designed for scientific research applications, such devices offer numerous benefits over conventional klystron technology. The IOT is much smaller than a klystron of similar power, and it requires less support circuitry. Because of the improved efficiency, power supply requirements are reduced, and device cooling is simplified.





**Figure 6.60** Schematic overview of the MSDC IOT or *constant efficiency amplifier*. (After [5].)

## 6.5 Constant Efficiency Amplifier

Because of the similarity between the spent electron beam in an IOT and that of a klystron or traveling-wave tube, it is possible to consider the use of a multistage depressed collector on an IOT to improve the operating efficiency [5]. This had been considered by Priest and Shrader [6] and by Gilmore [7], but the idea was rejected because of the complexity of the multistage depressed collector assembly and because the IOT already exhibited fairly high efficiency. Subsequent development by Symons [5, 8] has led to a prototype device (at this writing). An inductive output tube, modified by the addition of a multistage depressed collector, has the interesting property of providing linear amplification with (approximately) constant efficiency.

### 6.5.1 Theory of Operation

Figure 6.60 shows a schematic representation of the *constant efficiency amplifier* (CEA) [5]. The cathode, control grid, anode and output gap, and external circuitry are essentially identical with those of the IOT amplifier. Drive power introduced into the input cavity produces an electric field between the control grid and cathode, which draws current from the cathode during positive half-cycles of the input RF signal. For

operation as a linear amplifier, the peak value of the current—or more accurately, the fundamental component of the current—is made (as nearly as possible) proportional to the square root of the drive power, so that the product of this current and the voltage it induces in the output cavity will be proportional to the drive power.

Following the output cavity is a multistage depressed collector in which several typical electron trajectories are shown. These are identified by the letters *a* through *e*. The collector electrodes are connected to progressively lower potentials between the anode potential and the cathode potential so that more energetic electrons penetrate more deeply into the collector structure and are gathered on electrodes of progressively lower potentials.

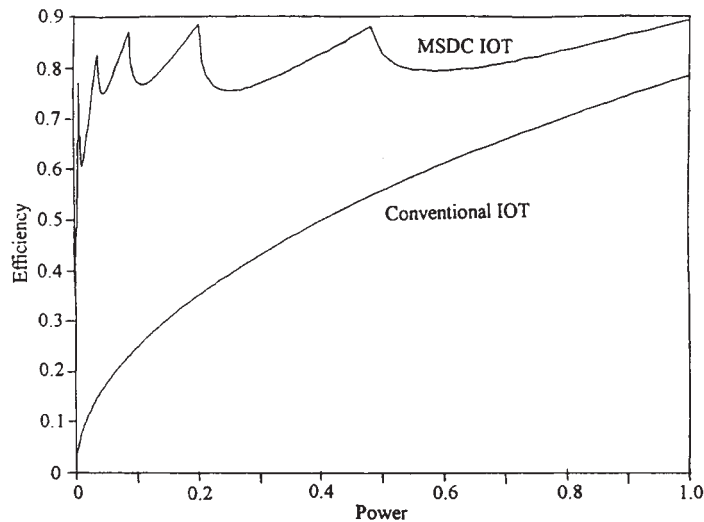
In considering the difference between an MSDC IOT and an MSDC klystron, it is important to recognize that in a class B device, no current flows during the portion of the RF cycle when the grid voltage is below cutoff and the output gap fields are accelerating. As a result, it is not necessary to have any collector electrode at a potential equal to or below cathode potential. At low output powers, when the RF output gap voltage is just equal to the difference in potential between the lowest-potential collector electrode and the cathode, all the current will flow to that electrode. Full class B efficiency is thus achieved under these conditions.

As the RF output gap voltage increases with increased drive power, some electrons will have lost enough energy to the gap fields so they cannot reach the lowest potential collector, and so current to the next-to-the-lowest potential electrode will start increasing. The efficiency will drop slightly and then start increasing again until all the current is just barely collected by the two lowest-potential collectors, and so forth.

Maximum output power is reached when the current delivered to the output gap is sufficient to build up an electric field or voltage that will just stop a few electrons. At this output power, the current is divided between all of the collector electrodes and the efficiency will be somewhat higher than the efficiency of a single collector, class B amplifier. Computer simulations have demonstrated that it is possible to select the collector voltages so as to achieve very nearly constant efficiency from the MSDC IOT device over a wide range of output powers [5].

The challenge of developing a multistage depressed collector for an IOT is not quite the same as that of developing a collector for a conventional klystron [8]. It is different because the dc component of beam current rises and falls in proportion to the square root of the output power of the tube. The dc beam current is not constant as it is in a klystron (or a traveling-wave tube for that matter). As a result, the energy spread is low because the output cavity RF voltage is low at the same time that the RF and dc beam currents are low. Thus, there will be small space-charge forces, and the beam will not spread as much as it travels deep into the collector toward electrodes having the lowest potential. For this reason, the collector is likely to be rather long and thin when compared to the multistage depressed collector for a conventional klystron, as described previously.

Figure 6.61 charts the calculated efficiency for an IOT with six depressed collector stages, set at 0.1, 0.2, 0.3, 0.45, 0.7, and 1.0 times the beam voltage (compared to that of a conventional IOT).

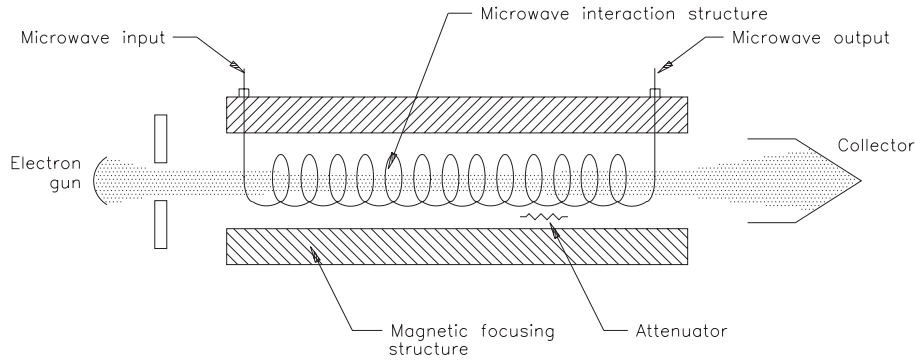


**Figure 6.61** Calculated efficiency of an MSDC IOT compared to an unmodified IOT. (After [5].)

## 6.6 Traveling Wave Tube

The traveling wave tube (TWT) is a linear-beam device finding extensive applications in communications and research. Power levels range from a few watts to 10 MW. Gain ranges from 40 to 70 dB for small drive signals. The TWT consists of four basic elements:

- *Electron gun.* The gun forms a high-current-density beam of electrons that interact with a wave traveling along the RF circuit to increase the amplitude of the RF signal. In a typical application, electrons are emitted from a cathode and converged to the proper beam size by focusing electrodes.
- *RF interaction circuit.* The RF wave is increased in amplitude as a result of interaction with the electron beam from the gun. The fundamental principle on which the TWT operates is that an electron beam, moving at approximately the same velocity as an RF wave traveling along a circuit, gives up energy to the RF wave.
- *Magnetic electron beam focusing system.* The beam size is maintained at the proper dimensions through the interaction structure by the focusing system. This may be accomplished by using either a permanent magnet or an electromagnetic focusing element.
- *Collector.* The electron beam is received at the collector after it has passed through the interaction structure. The remaining beam energy is dissipated in the collector.



**Figure 6.62** Basic elements of a traveling wave tube.

Figure 6.62 shows the basic elements of a TWT.

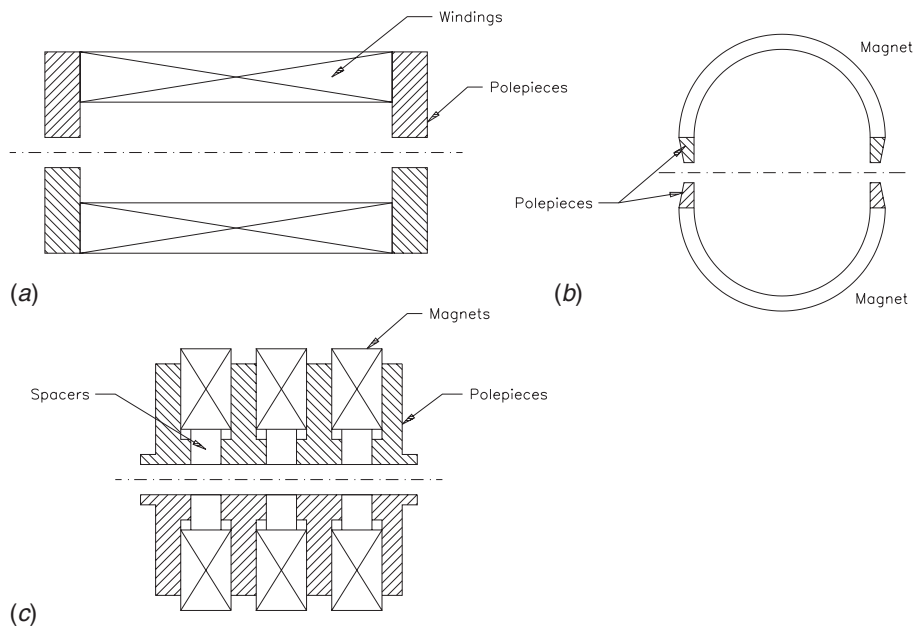
The primary differences between types of TWT devices involve the RF interaction structure employed. In Figure 6.62, the interaction structure is a helix. A variety of other structures may be employed, depending on the operating power and frequency. Three common approaches are used to provide the needed magnetic beam focusing. Illustrated in Figure 6.63, they are:

- Electromagnetic focusing, used primarily on high-power tubes, where tight beam focusing is required.
- Permanent-magnet focusing, used where the interaction structure is short.
- Periodic permanent-magnet focusing, used on most helix TWT and coupled-cavity tubes. The magnets are arranged with alternate polarity in successive cells along the interaction region.

### 6.6.1 Theory of Operation

The interaction structure acts to slow the RF signal so that it travels at approximately the same speed as the electron beam. Electrons enter the structure during both positive and negative portions of the RF cycle. Electrons entering during the positive portion are accelerated; those entering during the negative portion are decelerated. The result is the creation of *electron bunches* that produce an alternating current superimposed on the dc beam current. This alternating current induces the growth of an RF *circuit wave* that encourages even tighter electron bunching.

One or more *severs* are included to absorb reflected power that travels in a backward direction on the interaction circuit. This reflected power is the result of a mismatch between the output port and the load. Without the sever, regenerative oscillations could occur.



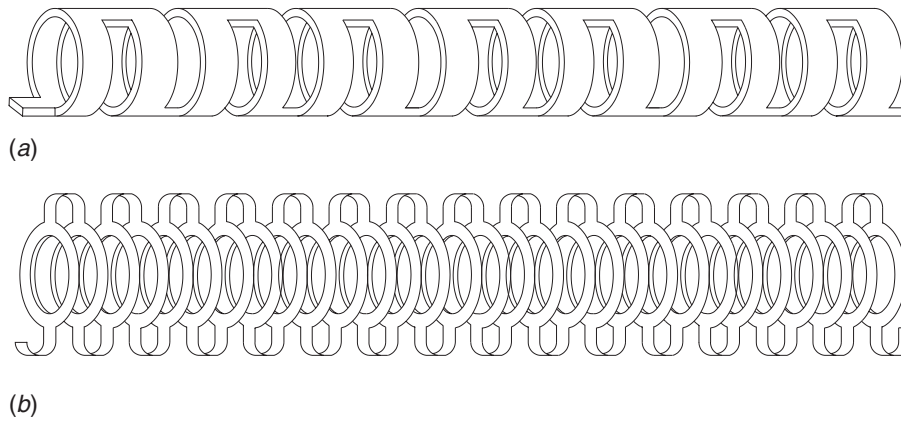
**Figure 6.63** Magnetic focusing for a TWT: (a) solenoid-type, (b) permanent-magnet-type, (c) periodic permanent-magnet structure.

At a given frequency, a particular level of drive power will result in maximum bunching and power output. This operating point is referred to as *saturation*.

### Interaction Circuit

The key to TWT operation lies in the interaction element. Because RF waves travel at the speed of light, a method must be provided to slow down the forward progress of the wave to approximately the same velocity as the electron beam from the cathode. The beam speed of a TWT is typically 10 to 50 percent the speed of light, corresponding to cathode voltages of 4 to 120 kV. Two mechanical structures commonly are used to slow the RF wave:

- **Helix circuit.** The helix is used where bandwidths of an octave or more are required. Over this range the velocity of the signal carried by the helix is basically constant with frequency. Typical operating frequencies range from 500 MHz to 40 GHz. Operating power, however, is limited to a few hundred watts. TWTs intended for higher-frequency operation may use a variation of the helix, shown in [Figure 6.64](#). The *ring-loop* and *ring-bar* designs permit peak powers of hundreds of kilowatts. The average power, however, is about the same as that of a conventional helix because the structure used to support the interaction circuit is the same.



**Figure 6.64** Helix structures for a TWT: (a) ring-loop circuit, (b) ring-bar circuit.

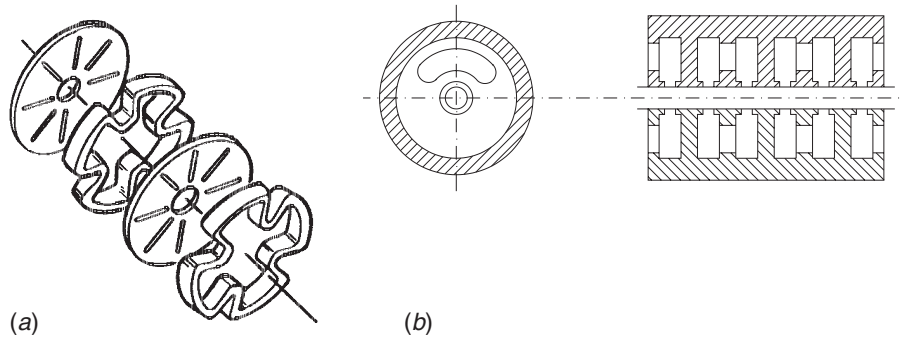
- *Coupled-cavity circuit.* The coupled-cavity interaction structure permits operation at high peak and average power levels, and moderate bandwidth (10 percent being typical). TWTs using coupled-cavity structures are available at operating frequencies from 2 to 100 GHz. The basic design of a coupled-cavity interaction circuit is shown in [Figure 6.65](#). Resonant cavities, coupled through slots cut in the cavity end walls, resemble a folded waveguide. Two basic schemes are used: the *cloverleaf* and the *single-slot space harmonic* circuit.

The cloverleaf, also known as the *forward fundamental* circuit, is used primarily on high-power tubes. The cloverleaf provides operation at up to 3 MW peak power and 5 kW average at S-band frequencies. The single-slot space harmonic interaction circuit is more common than the cloverleaf. The mechanical design is simple, as shown in the figure. The single-slot space harmonic structure typically provides peak power of up to 50 kW and average power of 5 kW at X-band frequencies.

### Pulse Modulation

The electron beam from the gun may be pulse-modulated using one of four methods:

- *Cathode pulsing.* The cathode is pulsed in a negative direction with respect to the grounded anode. This approach requires the full beam voltage and current to be switched.
- *Anode pulsing.* This approach is similar to cathode pulsing, except that the full beam voltage is switched between cathode potential and ground. The current switched, however, is only that value intercepted on the anode. Typically, the intercepted current is a few percent of the full beam potential.



**Figure 6.65** Coupled-cavity interaction structures: (a) forward fundamental circuit or “cloverleaf,” (b) single-slot space harmonic circuit.

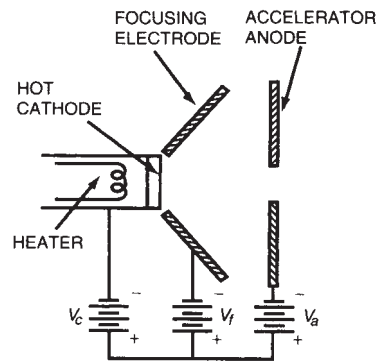
- *Focus electrode pulsing.* If the focus electrode, which normally operates at or near cathode potential, is biased negatively with respect to the cathode, the beam will be turned off. The voltage swing required is typically one-third of the full cathode voltage. This approach is attractive because the focus electrode draws essentially no current, making implementation of a switching modulator relatively easy.
- *Grid pulsing.* The addition of a grid to the cathode region permits control of beam intensity. The voltage swing required for the grid, placed directly in front of the cathode, is typically 5 percent of the full beam potential.

### Electron Gun

The electron gun of a TWT is a device that supplies the electron beam to the tube [9]. A schematic diagram of a generic electron gun is given in Figure 6.66. The device consists of a hot cathode heated by an electric heater, a negatively biased focusing electrode or *focuser*, and a positively biased *accelerating anode*. The cross-sectional view given in the figure can be a two-dimensional or three-dimensional coaxial structure [10, 11].

An axially symmetrical solid cylindrical electron beam is produced by the gun structure shown in Figure 6.66 if the structure is axially cylindrically symmetrical. If the middle of the hot cathode is made nonemitting and only the edge of the cathode is emitting, the cathode becomes an *annular cathode* [9]. The annular cathode produces a hollow beam. The annular electron beam can be used to reduce beam current for a given microwave output power.

If the gun structure shown in Figure 6.66 is two dimensional, then a ribbon-shaped electron beam is produced. A ribbon-shaped beam is used for a TWT of a two-dimensional structure.



**Figure 6.66** Generic TWT electron gun structure. (From [9]. Used with permission.)

If the angle of the focusing electrode against the axis of the electron beam is  $67.5^\circ$  and the anode is also tilted forward to produce a *rectilinear flow* (electron flow parallel to the  $z$  axis in Figure 6.66), then such an electron gun is termed the *Pierce gun*.

In practice, the hot cathode surface is curved as shown in Figure 6.67 to increase the electron emitting surface and to obtain a high-density electron beam.

### Beam Focusing

Electrons in an electron beam mutually repel each other by the electron's own coulomb force because of their negative charge [9]. In addition, the electron beam usually exists in proximity to the positively biased slow-wave structure, as shown in Figure 6.68. Therefore, the electron beam tends to diverge. The process of confining the electron beam within the desired trajectory against the mutual repulsion and diverging force from the slow-wave structure is termed *electron beam focusing*.

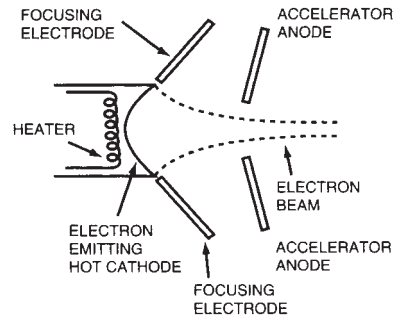
The electron beam in a TWT is usually focused by a dc magnetic flux applied parallel to the direction of the electron beam, which is coaxial to the slow-wave transmission line. Variations on this basic technique include:

- *Brillouin flow*, where the output of the electron gun is not exposed to the focusing magnetic flux [12].
- *Immersed flow*, where the electron gun itself is exposed to and unshielded from the focusing para-axial longitudinal magnetic flux [12].
- *Generic flow*, where the electron gun is not shielded from the focusing magnetic flux, and focusing flux is not para-axia. (In other words, neither Brillouin nor immersed flow.)

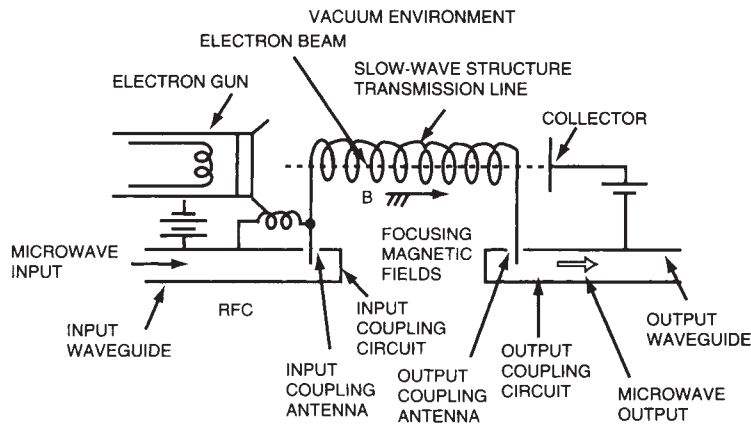
### Collector Assembly

Various configurations are used for the collector assembly of a TWT. Figure 6.69 shows a selection of the more common, including [9]:





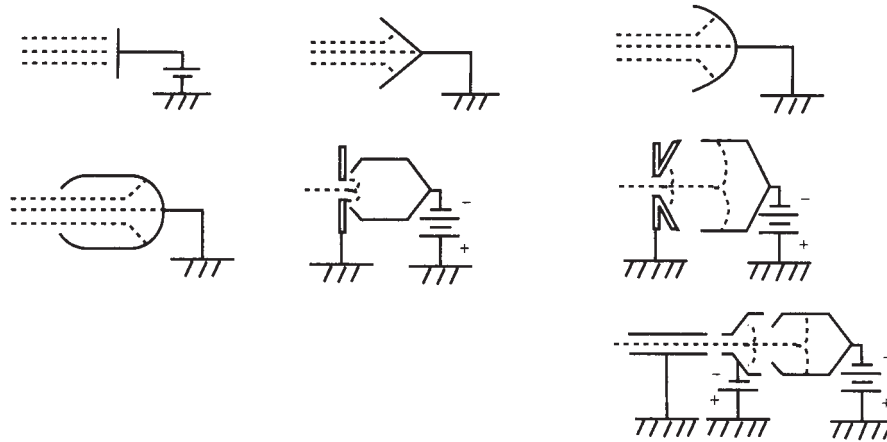
**Figure 6.67** Cross-sectional view of a TWT electron gun with a curved hot cathode. (From [9]. Used with permission.)



**Figure 6.68** Generic configuration of a traveling wave tube. (From [9]. Used with permission.)

- Plate collector
- Cone collector
- Curved cone
- Cylinder collector
- Depressed potential cylinder
- Two-stage collector
- Three-stage collector

Cooling options include conduction, air, and water.



**Figure 6.69** Cross-sectional view of various collector configurations for a TWT. (From [9]. Used with permission.)

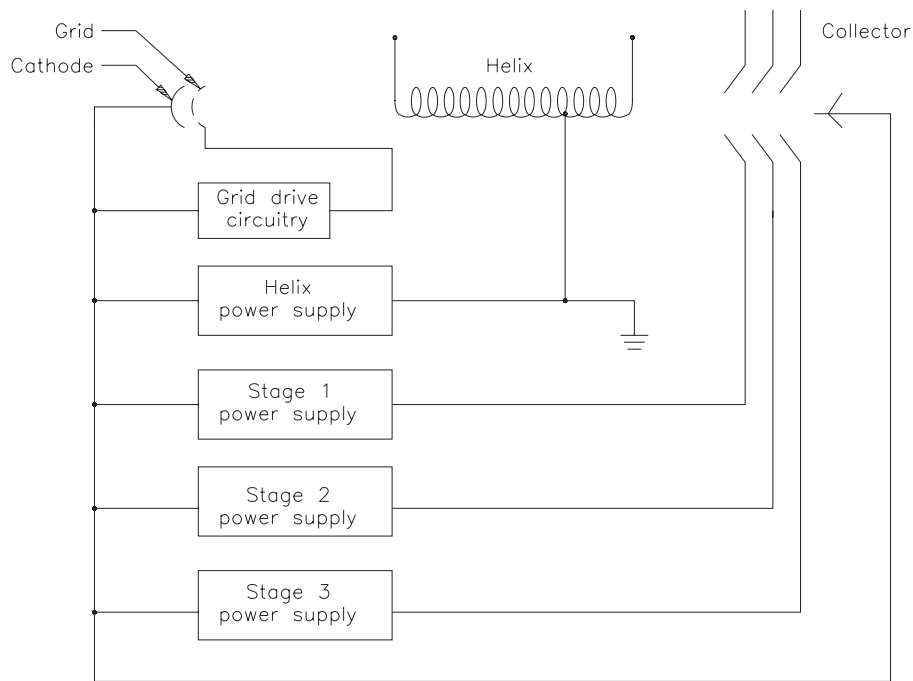
Cooling of a low-power TWT is accomplished by clamping the tube to a metal baseplate, mounted in turn on an air- or liquid-cooled heat sink. Coupled-cavity tubes below 1 kW average power are convection-cooled by circulating air over the entire length of the device. Higher-power coupled-cavity tubes are cooled by circulating liquid over the tube body and collector.

### 6.6.2 Operating Efficiency

Efficiency is not one of the TWT's strong points. Early traveling wave tubes offered only about 10 percent dc-to-RF efficiency. Wide bandwidth and power output are where the TWT shines. TWT efficiency may be increased in two basic ways: (1) collector depression for a single-stage collector, or (2) use of a multistage collector.

Collector depression refers to the practice of operating the collector at a voltage lower than the full beam voltage. This introduces a potential difference between the interaction structure and the collector, through which electrons pass. The amount by which a single-stage collector can be depressed is limited by the remaining energy of the slowest electrons. In other words, the potential reduction can be no greater than the amount of energy of the slowest electrons, or they will turn around and reenter the interaction structure, causing oscillations.

By introducing multiple depressed collector stages, still greater efficiency can be realized. This method provides for the collection of the slowest electrons at one collector potential, while allowing those with more energy to be collected on other stages that are depressed still further. This approach, similar to the MSDC design discussed previously, is illustrated in [Figure 6.70](#).



**Figure 6.70** Power supply configuration for a multistage depressed collector TWT.

### 6.6.3 Operational Considerations

Although traveling wave tubes offer numerous benefits to the end user, they are not without their drawbacks.

#### Intermodulation Distortion

TWTs are susceptible to intermodulation (IM) distortion when multiple carriers are introduced, as in double illuminated or multiple SCPC (*single channel per carrier*) satellite transponders. These IM products may be found at frequencies that are displaced from the fundamental carriers by the difference in frequency between them. When multiple carriers are present, the potential for IM exists. This potential is reduced by operating the TWT below saturation. Power must be reduced (backed off) in proportion to the number of carriers and their relative power.

#### Second-Harmonic Content

Because of the wide bandwidth and nonlinear operating characteristics under saturation conditions, a TWT may generate significant second-harmonic energy. It is not uncommon to measure second-harmonic energy at the output of a TWT that is down only 10 dB from the operating carrier.

Reduction of harmonic content usually involves injecting a coherent harmonic signal with controlled phase and amplitude along with the fundamental carrier so that they interact, minimizing harmonic energy at the output of the device.

### **AM/PM Conversion**

AM/PM conversion is the change in phase angle between the input and output signals as the input varies in amplitude. The root cause of this distortion in a TWT centers on the reduction of electron beam velocity as the input signal level increases. This causes a greater energy exchange between the electron beam and the RF wave. At a level 20 dB below the input power required for saturation, AM/PM conversion is negligible. At higher levels, AM/PM distortion may increase.

### **Phase Variation**

When the velocity of the electron beam in the TWT is changed, the phase of the output signal also will vary. The primary causes of beam velocity variations include changes in one or more of the following:

- Cathode temperature
- Grid voltage
- Anode voltage
- Cathode voltage

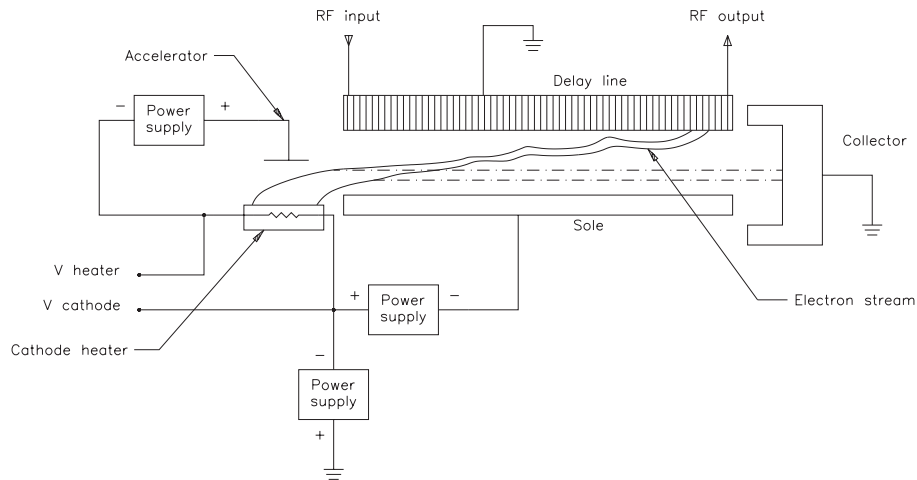
The TWT power supply must be well regulated (to less than 0.2 percent) to prevent beam velocity changes that may result in output signal phase variations.

## **6.7 Crossed-Field Tubes**

A crossed-field microwave tube is a device that converts dc into microwave energy using an electronic energy-conversion process. These devices differ from *beam tubes* in that they are *potential-energy converters*, rather than kinetic-energy converters. The term *crossed field* is derived from the orthogonal characteristics of the dc electric field supplied by the power source and the magnetic field required for beam focusing in the interaction region. This magnetic field typically is supplied by a permanent-magnet structure. Such devices also are referred to as *M-tubes*.

Practical devices based on the crossed-field principles fall into two broad categories:

- *Injected-beam crossed-field tubes*. The electron stream is produced by an electron gun located external to the interaction region, similar to a TWT. The concept is illustrated in [Figure 6.71](#).
- *Emitting-sole tubes*. The electron current for interaction is produced directly within the interaction region by secondary electron emissions, which result when some electrons are driven to the negative electrode and allowed to strike it. The



**Figure 6.71** Linear injected-beam microwave tube.

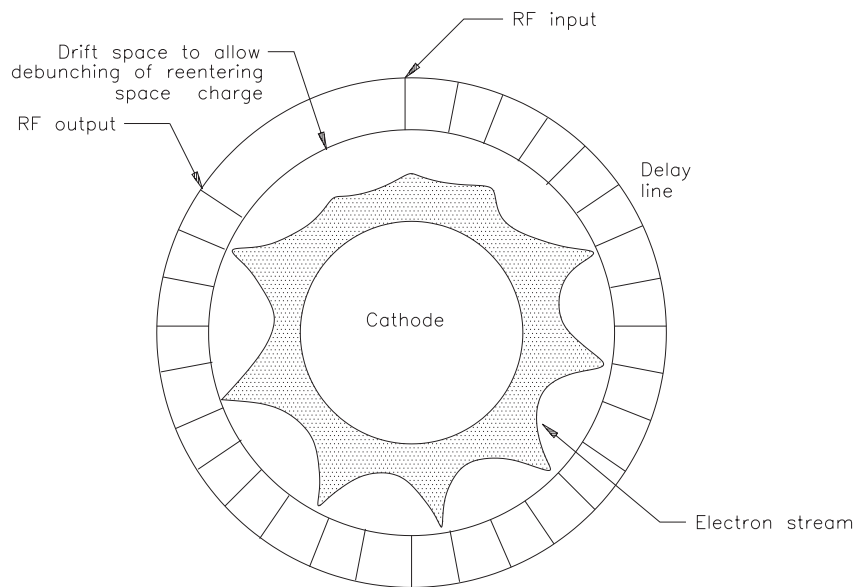
negative electrode is formed using a material capable of producing significant numbers of secondary-emission electrons. The concept is illustrated in [Figure 6.72](#).

### 6.7.1 Magnetron

The magnetron encompasses a class of devices finding a wide variety of applications. Pulsed magnetrons have been developed that cover frequency ranges from the low UHF band to 100 GHz. Peak power from a few kilowatts to several megawatts has been obtained. Typical overall efficiencies of 30 to 40 percent may be realized, depending on the power level and operating frequency. CW magnetrons also have been developed, with power levels of a few hundred watts in a tunable tube, and up to 25 kW or more in a fixed-frequency device. Efficiencies range from 30 percent to as much as 70 percent.

The magnetron operates electrically as a simple diode. Pulsed modulation is obtained by applying a negative rectangular voltage waveform to the cathode with the anode at ground potential. Operating voltages are less critical than for beam tubes; line-type modulators often are used to supply pulsed electric power. The physical structure of a conventional magnetron is shown in [Figure 6.73](#).

High-power pulsed magnetrons are used primarily in radar systems. Low-power pulsed devices find applications as beacons. Tunable CW magnetrons are used in ECM (electronic countermeasures) applications. Fixed-frequency devices are used as microwave heating sources.



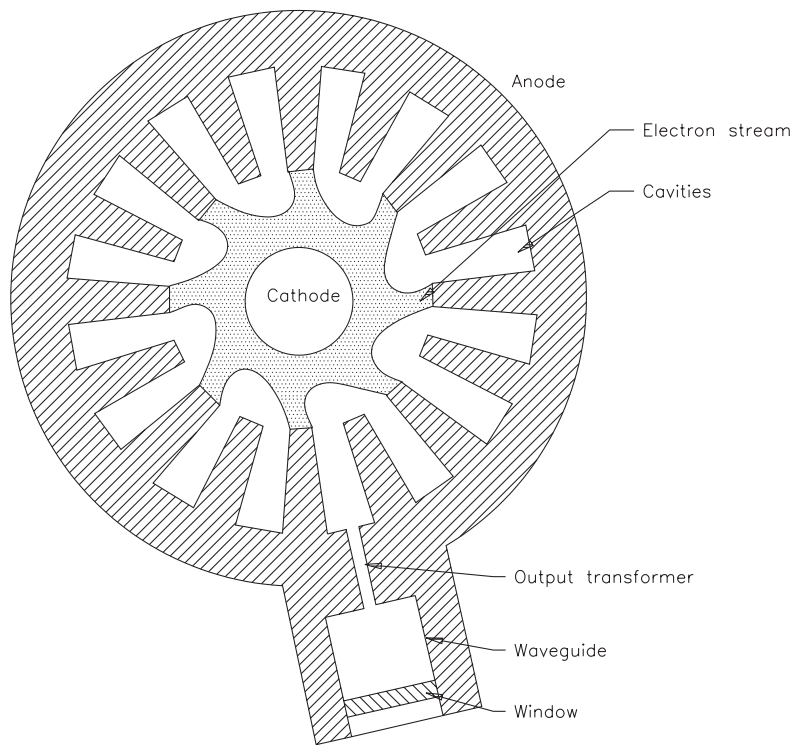
**Figure 6.72** Reentrant emitting-sole crossed-field amplifier tube.

Tuning of conventional magnetrons is accomplished by moving capacitive tuners or by inserting symmetrical arrays of plungers into the inductive portions of the device. Tuner motion is produced by a mechanical connection through flexible bellows in the vacuum wall. Tuning ranges of 10 to 12 percent of bandwidth are possible for pulsed tubes, and as much as 20 percent for CW tubes.

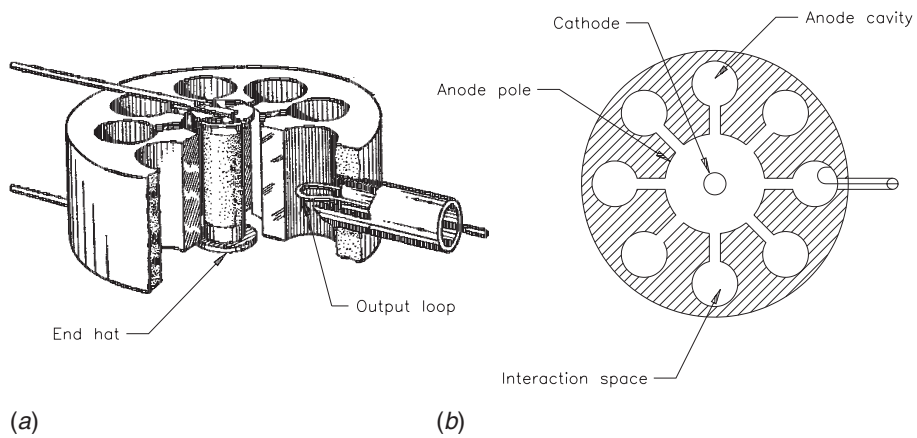
### Operating Principles

Most magnetrons are built around a cavity structure of the type shown in [Figure 6.74](#). The device consists of a cylindrical cathode and anode, with cavities in the anode that open into the cathode-anode space—the *interaction space*—as shown. Power can be coupled out of the cavities by means of a loop or a tapered waveguide.

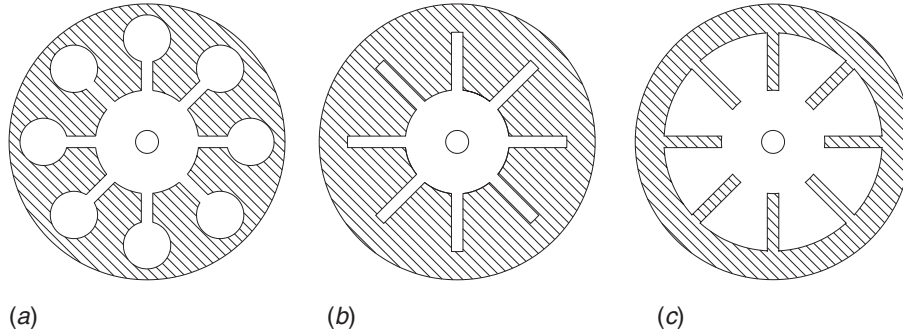
Cavities, together with the spaces at the ends of the anode block, form the resonant system that determines the frequency of the generated oscillations. The actual shape of the cavity is not particularly important, and various types are used, as illustrated in [Figure 6.75](#). The oscillations associated with the cavities are of such a nature that alternating magnetic flux lines pass through the cavities parallel to the cathode axis, while the alternating electric fields are confined largely to the region where the cavities open into the interaction space. The most important factors determining the resonant frequency of the system are the dimensions and shape of the cavities in a plane perpendicular to the axis of the cathode. Frequency also is affected by other factors such as the end space and the axial length of the anode block, but to a lesser degree.



**Figure 6.73** Conventional magnetron structure.



**Figure 6.74** Cavity magnetron oscillator: (a) cutaway view, (b) cross section view perpendicular to the axis of the cathode.



**Figure 6.75** Cavity magnetron oscillator anode: (a) hole-and-slot type, (b) slot type, (c) vane type.

The magnetron requires an external magnetic field with flux lines parallel to the axis of the cathode. This field usually is provided by a permanent-magnet or electromagnet.

The cathode is commonly constructed as a cylindrical disk.

### Coaxial Magnetron

The frequency stability of a conventional magnetron is affected by variations in the load impedance and by cathode-current fluctuations. Depending on the extent of these two influences, the magnetron occasionally may fail to produce a pulse. The coaxial magnetron minimizes these effects by using the anode geometry shown in Figure 6.76. Alternate cavities are slotted to provide coupling to a surrounding coaxial cavity.

The oscillating frequency is controlled by the combined vane system and the resonant cavity. Tuning may be accomplished through the addition of a movable end plate in the cavity, as shown in Figure 6.77.

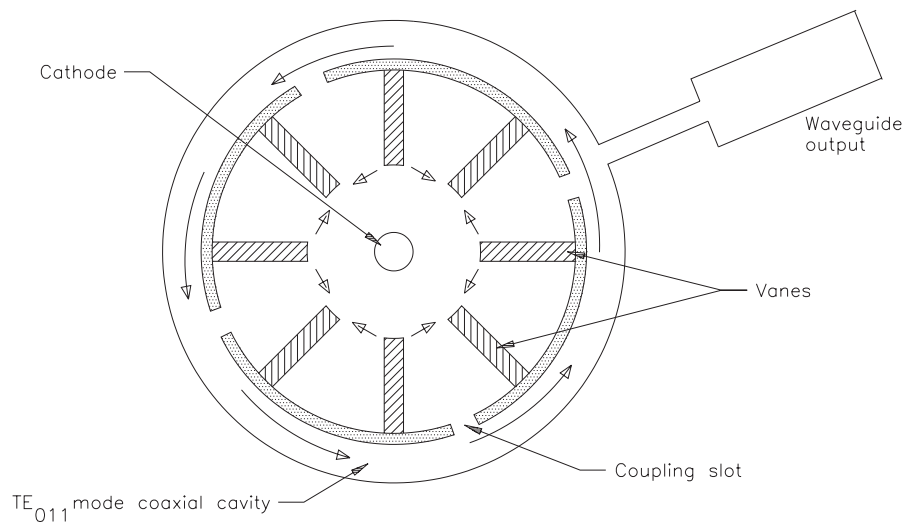
### Frequency-Agile Magnetron

Tubes developed for specialized radar and ECM applications permit rapid tuning of the magnetron. A conventional device may be tuned using one of the following methods:

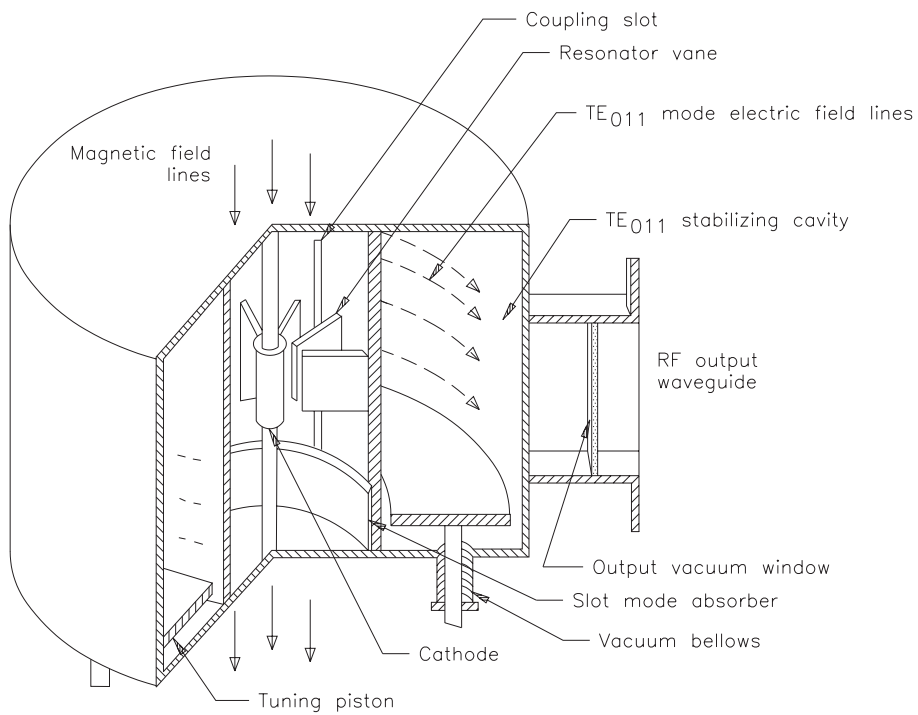
- A rapidly rotating capacitive element. Tubes of this type are referred to as *spin-tuned magnetrons*.
- A hydraulic-driven tuning mechanism. Tubes of this type are referred to as *mechanically tuned magnetrons*.

Electronic tuning of magnetrons is also possible, with tuning rates as high as several megahertz per microsecond.

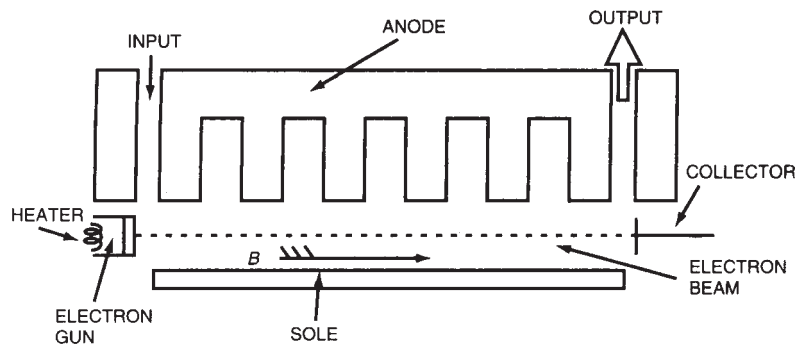




**Figure 6.76** Structure of a coaxial magnetron.



**Figure 6.77** Structure of a tunable coaxial magnetron.



**Figure 6.78** Cross-sectional view of a linear magnetron. (From [13]. Used with permission.)

### Linear Magnetron

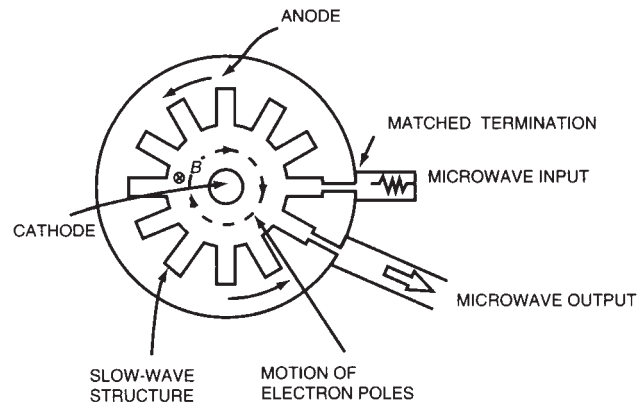
Although the most common types of magnetrons are radial in nature, the *linear magnetron* and *inverted magnetron* may also be used, depending upon the application [13]. A cross-sectional view of a linear magnetron is given in Figure 6.78. Shown in the figure is the *O-type* linear magnetron, in which the electron beam emitted from the electron gun is focused by a longitudinally applied dc magnetic flux density ( $B$ ), as in the case of the traveling wave tube.

As shown in the figure, a number of slots are included in the basic structure. These slots are cut 1/4-wavelength deep, functioning as quarter-wave cavity resonators. This structure forms a series of microwave cavity resonators coupling to an electron beam, in a similar manner to the multicavity klystron. The velocity modulated electrons are bunched, and the tightly bunched electrons produce amplified microwave energy at the output cavity, which is coupled to an external circuit. The linear magnetron typically offers high gain, but narrow frequency bandwidth.

### 6.7.2 Backward Wave Oscillator

In a traveling wave tube, if the microwave signal to be amplified is propagating in the slow-wave structure backwardly to the direction of the electron beam, the device is termed a *backward wave oscillator* (BWO) [13]. Microwaves traveling in a backward direction carry positive feedback energy toward the electron gun and yield stronger velocity modulation and bunching. Thus, the system is inherently an oscillator rather than a stable amplifier. The input is typically terminated by an impedance-matched reflectionless termination device. The oscillation frequency is a function of the speed of the electrons and the time constant of the feedback mechanism. The speed of electron motion is controlled by the anode voltage.

An *M-type* radial BWO is shown in Figure 6.79. The direction of electron pole motion and the direction of microwave propagation along the annular reentrant type



**Figure 6.79** Functional schematic of the M-type radial BWO. (From [13]. Used with permission.)

slow-wave structure are opposite each other. It should be noted that the depths of the slits cut in the inner surface of the anode is very shallow—much less than 1/4-wavelength deep. In other words, the slits are not in resonance; they are not cavity resonators, as is the case of a magnetron. Rather, the slits are nonresonating, as in the case of a TWT. In the M-type radial BWO, the electron beam is focused by a magnetic flux density applied perpendicular to the beam, as seen from [Figure 6.79](#).

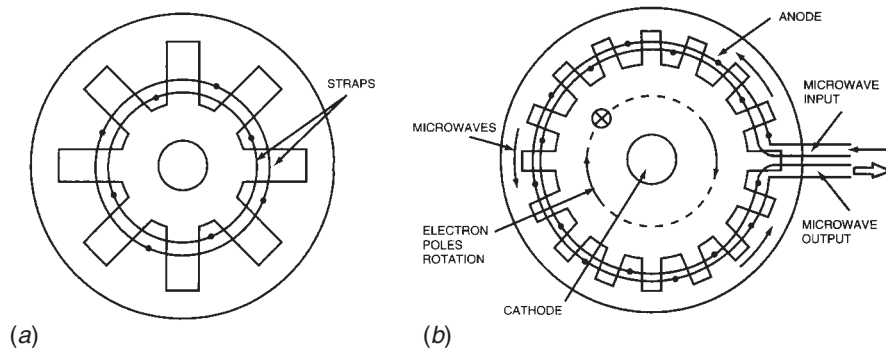
An M-type radial BWO is sometimes termed the *Carcinotron*, a trade name. A key feature of the Carcinotron is its wide voltage tunability over a broad frequency range.

### 6.7.3 Strap-Fed Devices

A radial magnetron can be configured so that every other pole of the anode resonators are conductively tied for microwave potential equalization, as shown in [Figure 6.80a](#) [13]. These conducting tie rings are termed *straps*; the technique of using strap rings is termed *strapping*. Strapping ensures good synchronization of microwaves in the magnetron resonators with the rotation of electron poles.

The technique of strapping is extended and modified for an M-type radial BWO, as shown in [Figure 6.80b](#). Strapping rings tie every other pole of the radial slow-wave structure, as in the case of a strapped radial magnetron, but the strapping rings are no longer reentrant. Microwave energy to be amplified is fed to the strap at one end, and the amplified output is extracted from the other end. This type of electron tube is termed a *strap-fed device*.

If an M-type radial BWO is strapped, usually it does not start oscillation by itself. But, if microwave energy is fed through the strap from the outside using an external microwave power source to the microwave input, then the oscillation starts—and even if



**Figure 6.80** Strap-fed devices: (a) strapped radial magnetron, (b) nonreentrant strapping of a BWO. (From [13]. Used with permission.)

the exciter source is turned off, the oscillation continues. This type of M-type radial BWO is termed the *platinotron* [14].

In a platinotron, if the output of the tube is fed back to the input through a high- $Q$  cavity resonator, it becomes a self-starting oscillator. The oscillation frequency is stabilized by the high- $Q$  cavity resonator. This type of high-power frequency stabilized strapped radial BWO is termed the *stabilotron* [14]. The operating powers are at kilowatt and megawatt levels.

Performance of the platinotron depends on, among other things, the design of the slow-wave structure. For example, the interdigital slow-wave structure as shown in Figure 6.80 has a limited power handling capability and frequency bandwidth. Design of a slow-wave structure with greater power handling capacity and stability, with broader frequency bandwidth, is possible. For example, instead of an anode with an interdigital slow-wave structure, the anode could be made of an annular open conducting duct, loaded with a number of pairs of conducting posts across the open duct. Strapping is done at every other tip of the pairs of conducting posts. This type of strapping loads the slow-wave structure, stabilizing it and preventing oscillation. The structure of the anode with an annular duct and pairs of posts increases the power handling capability. This type of loaded radial BWO is termed the *amplitron* [14, 10]. The amplitron is capable of amplifying high-power microwave signals with pulses and continuous waves. It is used for long-range pulsed radar transmitter amplifiers and industrial microwave heating generators. The operating power levels range from kilowatt to megawatt levels.

### 6.7.4 Gyrotron

The *gyrotron* is a *cyclotron resonance maser*.<sup>4</sup> The device includes a cathode, collector, and circular waveguide of gradually varying diameter. Electrons are emitted at the cathode with small variations in speed. The electrons then are accelerated by an electric field and guided by a static magnetic field through the device. The nonuniform induction field causes the rotational speed of the electrons to increase. The linear velocity of the electrons, as a result, decreases. The interaction of the microwave field within the waveguide and the rotating (helical) electrons causes bunching similar to the bunching within a klystron. A decompression zone at the end of the device permits decompression and collection of the electrons.

The power available from a gyrotron is 100 times greater than that possible from a classic microwave tube at the same frequency. Power output of 100 kW is possible at 100 GHz, with 30 percent efficiency. At 300 GHz, up to 1.5 kW may be realized, but with only 6 percent efficiency.

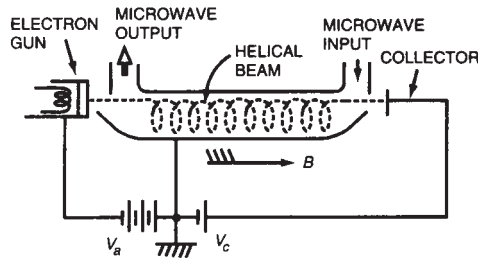
#### Theory of Operation

The trajectory of an electron in an electron beam focused by a longitudinally applied magnetic field is a helix [13]. If the electron velocity, electron injection angle, and applied longitudinal magnetic flux density are varied, then an electron beam of helical form with different size and pitch will be formed. A coil-shaped electron beam will be produced by adjusting the acceleration voltage, applied magnetic flux density, and the electron injection angle to the focusing magnetic field. The coil of the electron beam can be a simple single coil, or—depending on the adjustment of the aforementioned three parameters—it can be an electron beam of a double coil, or a large coil made of thin small coils. In the case of the double-coil trajectory, the large coil-shaped trajectory is termed the *major orbit* and smaller coil trajectory is termed the *minor orbit*.

If a single coil-shaped electron beam is launched in a waveguide, as shown in [Figure 6.81](#), then microwaves in the waveguide will interact with the helical beam. This type of vacuum tube is termed the *helical beam tube* [14]. In this class of device, a single-coil helical beam is launched into a  $TE_{10}$  mode rectangular waveguide. Inside the waveguide, microwaves travel from right to left and the helical beam travels in an opposite direction. Therefore, the microwave-electron beam interaction is of the *backward wave* type. If the microwave frequency, the focusing magnetic flux density  $B$ , and the acceleration voltage  $V_a$  are properly adjusted, this device will function as a *backward wave amplifier*. Electrons in the helical beam interact with the transverse microwave electric fields and are velocity modulated at the left-hand side of the waveguide as the beam enters into the waveguide. The velocity modulated electrons in the helical beam are bunched as they travel toward the right. If the alternating microwave electric field syn-

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4 Maser is an acronym for *microwave amplification by simulated emission of radiation*. Maser is a general class of microwave amplifiers based on molecular interaction with electromagnetic radiation.



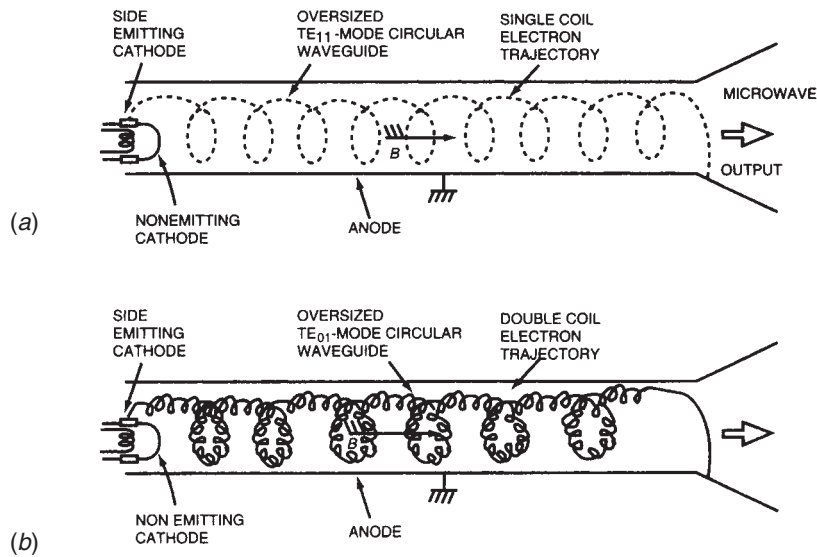
**Figure 6.81** Basic structure of a helical beam tube. (From [13]. Used with permission.)

chronizes its period and phase with the helical motion of bunched electrons so that the electrons always receive retardation from microwave transverse electric fields, then the electrons lose their kinetic energy and the microwave signal gains in electric field energy according to the principle of kinetic energy conservation. Thus, the amplified microwave power emerges at the waveguide output at the left (because the microwaves travel backward).

In [Figure 6.81](#), if the microwave input port and the output port are interchanged with each other, then the system becomes a *forward wave amplifier*. Such a forward wave amplifier is termed a *peniotron* [14].

If the electron gun is modified to incorporate a side emitting cathode and the waveguide is changed to  $TE_{11}$  mode oversized circular waveguide, as shown in [Figure 6.82a](#), the gyrotron is formed. In this device, both ends of the waveguide are open and there are sufficient reflections in the waveguide for positive feedback. The gyrotron is, thus, a forward wave oscillator.

A *double-coil helical beam gyrotron* is shown in [Figure 6.82b](#). The device is formed by readjusting the anode voltage and the focusing flux density so that the electron beam is made into a double helical coil (as shown in the figure), and operating the oversized circular waveguide in the  $TE_{01}$  mode. In the  $TE_{01}$  mode, the microwave transverse electric fields exist as concentric circles. Therefore, the tangential electric fields interact with electrons in the small coil trajectory. The alternating tangential microwave electric fields are made to synchronize with the tangential motion of electrons in the minor coil-shaped trajectory. Thus, electron velocity modulation takes place near the cathode and bunching takes place in the middle of the tube. Microwave kinetic energy transfer takes place as the beam approaches the right. The focusing magnetic flux density  $B$  is applied only in the interaction region. Therefore, if the electron beam comes out of the interaction region, it is defocused and collected by the anode waveguide (as depicted in [Figure 6.82b](#)). If the circular waveguide is operated in an oversized  $TE_{11}$  mode, with the double-coil helical beam, then the device is referred to as a *tornadotron* [14]. Microwave-electron interaction occurs between the parallel component of tangential motion of the small helical trajectory and the  $TE_{11}$  mode microwave electric field. If the phase of microwave electric field decelerates bunched electrons, then the lost kinetic energy of the bunched electrons is transferred to the microwave signal and oscillation begins.



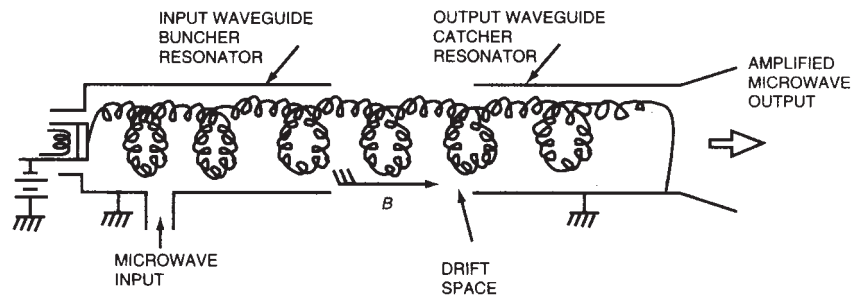
**Figure 6.82** Functional schematic diagram of the gyrotron: (a) single coiled helical beam gyrotron, (b) electron trajectory of double-coil helical beam gyrotron. (From [13]. Used with permission.)

### Gyrotron Design Variations

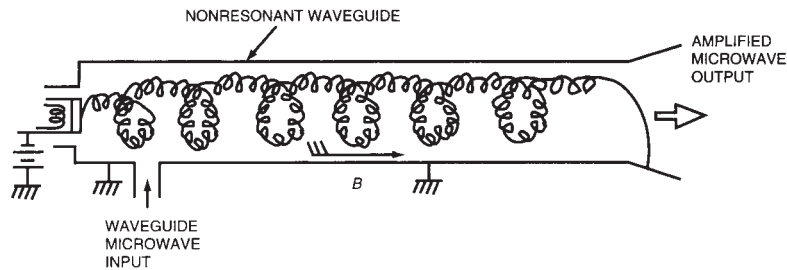
The gyrotron exists in a number of design variations, each optimized for a particular feature or application [13, 15, 16].

When the gyrotron circular waveguide is split as shown in Figure 6.83, the tube is termed the *gyroklystron amplifier* [13]. Both waveguides resonate to the input frequency, and there are strong standing waves in both waveguide resonators. The input microwave signal to be amplified is fed through a side opening to the input waveguide resonator. This is the *buncher resonator*, which functions in a manner similar to the klystron. The buncher resonator imparts velocity modulation to gyrating electrons in the double helical coil-shaped electron beam. There is a drift space between the buncher resonator and the catcher resonator at the output. While drifting electrons bunch and bunched electrons enter into the output waveguide catcher resonator, electron speed is adjusted in such a manner that electrons are decelerated by the resonating microwave electric field. This lost kinetic energy in bunched electrons is transformed into microwave energy and microwaves in the catcher resonator are, thus, amplified. The amplified power appears at the output of the tube.

If the gyrotron waveguide is an unsplit one-piece waveguide that is impedance-matched and not resonating, as shown in Figure 6.84, the tube is termed the *gyrotron traveling wave tube amplifier* [13]. In this tube, the input microwaves are fed through an opening in the waveguide near the electron gun. Microwaves in the wave-



**Figure 6.83** Basic structure of the gyrokystron amplifier. (From [13]. Used with permission.)

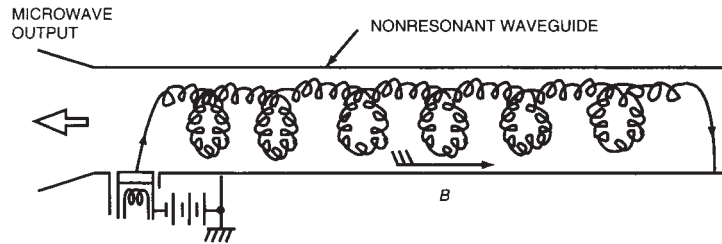


**Figure 6.84** Basic structure of the gyrokystron traveling wave tube amplifier. (From [13]. Used with permission.)

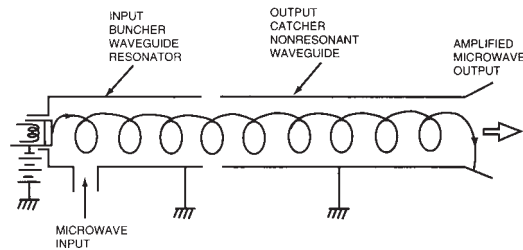
guide are amplified gradually as they travel toward the output port by interacting with the double-coiled helical electron beam, which is velocity-modulated and bunched. There are no significant standing waves in the waveguide. Microwaves grow gradually in the waveguide as they travel toward the output port as a result of interaction with electrons.

If the electron gun of the gyrotron is moved to the side of the waveguide and microwave power is extracted from the waveguide opening in proximity to the electron gun, as shown in Figure 6.85, then the device is termed a *gyrotron backward oscillator* [13]. The principle involved is similar to the backward wave oscillator, and the process of velocity modulation, drifting, bunching, and catching is similar to that of the klystron. Microwave energy induced in the waveguide travels in both directions, but the circuit is adjusted to emphasize the waves traveling in a backward direction. The backward waves become the output of the tube and, at the same time, carry the positive feedback energy to the electrons just emitted and to be velocity-modulated. The system, thus, goes into oscillation.





**Figure 6.85** Basic structure of the gyrotron backward oscillator. (From [13]. Used with permission.)



**Figure 6.86** Basic structure of the gyrotwystron amplifier. (From [13]. Used with permission.)

If the gyrotron waveguide is split into two again, but this time the input side waveguide is short and the output side waveguide is long, as shown in Figure 6.86, then the tube is termed a *gyrotwystron amplifier* [13]. This device is a combination of the gyrokystron and gyrotron traveling wave tube amplifier, thus the name gyrotwystron amplifier. The input side waveguide resonator is the same as the input resonator waveguide of a gyrokystron. There are strong standing waves in the input bunched-waveguide resonator. There is no drift space between the two waveguides. The output side waveguide is a long impedance-matched waveguide and there is no microwave standing wave in the waveguide (a traveling-wave waveguide). As microwaves travel in the waveguide, they interact with bunched electrons and the microwaves grow as they move toward the output port.

## 6.8 Other Microwave Devices

There are a number of variations on the basic microwave devices outlined previously in this chapter. Some find widespread usage, others have little commercial interest.

Among the important specialty device classifications are *quasiquantum devices* and modified klystrons.

### 6.8.1 Quasiquantum Devices

In a gyrotron, if electrons are accelerated by extremely high voltage, they become relativistic [13]. That is, the mass of an electron becomes a function of the velocity as,

$$m = \frac{m_0}{\sqrt{1 - (c/v)^2}} \quad (6.3)$$

Where:

$m$  = the relativistic mass of an electron

$m_0$  = the static mass of an electron

$c$  = the speed of light in vacuum

$v$  = the speed of the electron in question

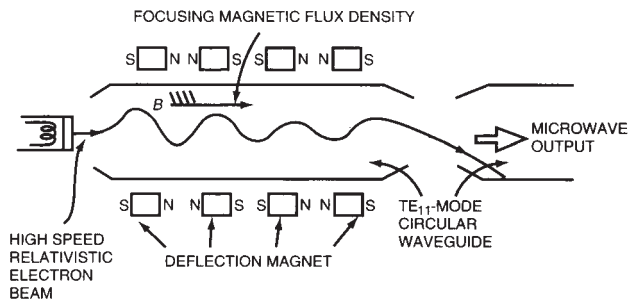
The energy states of electrons are specified by a set of quantum numbers, and the transition of energy states occurs only between those numbers so described. A set of quantum numbers specifies the high-energy orbit and low-energy orbit of an electron.

One device based on this principle is the *free electron laser*, or the *ubitron* [13]. A schematic diagram of the device is given in [Figure 6.87](#). A high-speed relativistic electron beam is emitted from an electron gun focused by a longitudinally applied dc magnetic flux density  $B$  and is periodically deflected by magnetic means. The repetitious deflections create among relativistic electrons high-energy states and low-energy states. If the high-energy electrons in the deflection waveguides are stimulated by the resonance frequency of the waveguide resonator, then the *downward transition* (the transition of electrons in a high-energy state to a low-energy state) occurs. Microwave emissions result because of the energy transitions at the stimulation frequency.

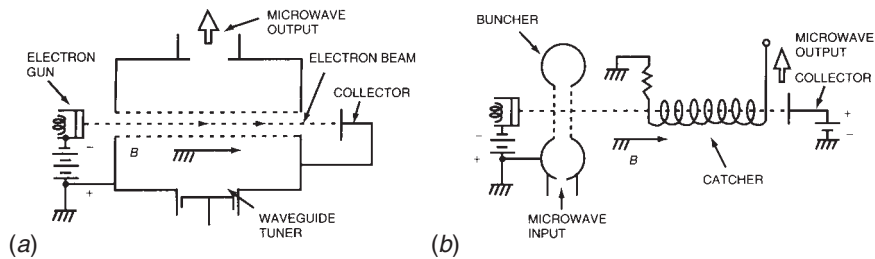
The ubitron operates at millimeter or submillimeter wave frequencies, and typically at high power levels.

### 6.8.2 Variations on the Klystron

Because the multiple cavities of a conventional klystron are difficult to fabricate at millimeter wavelengths, variations on the basis design have been produced [13]. Instead of using multiple cavity resonators, the cavities can instead be combined into a single cavity. Such a design can be accomplished through the use of ladder-shaped grids, as shown in [Figure 6.88a](#) by the dashed lines with the single cavity. This type of klystron is referred to as the *laddertron* [14]. Because of the ladder structure, a standing wave will exist on the ladder line. Velocity modulation results near the electron gun and bunching begins near the middle of the electron stream. Catching is done in the ladder structure near the collector. Because this device is a one-cavity resonator,



**Figure 6.87** Basic structure of the ubitron. (From [13]. Used with permission.)



**Figure 6.88** Functional schematic diagrams of modified klystrons: (a) laddertron, (b) twystron. (From [13]. Used with permission.)

there is built-in positive feedback. Oscillation, therefore, begins in a manner similar to a reflex klystron, also a single cavity tube.

At millimeter wavelengths, a dominant mode cavity resonator becomes very small and loses its power-handling capability. In a laddertron, however, the cavity resonator is a multiple higher-mode resonator. Therefore, the  $Q$  of the cavity is high and the size of the cavity resonator is reasonably large. This being the case, the laddertron can handle tens of watts of power at frequency as high as 50 GHz.

The catcher of a two-cavity klystron amplifier can be replaced by the slow-wave structure of a traveling wave tube, as shown in Figure 6.88b. This type of tube is termed the *twystron* [14]. The slow-wave structure provides a broader frequency bandwidth than a regular two-cavity klystron. A microwave input signal fed into the buncher cavity results in velocity modulation of the electron beam. Bunching occurs while the beam drifts, and the bunched electrons induce a microwave voltage in the slow-wave structure. The electron beam is focused by the use of longitudinally applied magnetic flux density  $B$ .

Commercial tweekstrons typically operate at 2–6 GHz and are used in pulsed radar transmitter power amplifiers. Pulsed peak output powers range from 1 to 7 MW (pulse width of 10–50  $\mu\text{s}$ ) [10].

## 6.9 Microwave Tube Life

Any analysis of microwave tube life must first identify the parameters that define *life*. The primary *wear-out* mechanism in a microwave power tube is the electron gun at the cathode. In principle, the cathode eventually will evaporate the activating material and cease to produce the required output power. Tubes, however, rarely fail because of low emission, but for a variety of other reasons that are usually external to the device.

Power tubes designed for microwave applications provide long life when operated within their designed parameters. The point at which the device fails to produce the required output power can be predicted with some accuracy, based on design data and in-service experience. Most power tubes, however, fail because of mechanisms other than predictable chemical reactions inside the device itself. External forces, such as transient overvoltages caused by lightning, cooling system faults, and improper tuning, more often than not lead to the failure of a microwave tube.

### 6.9.1 Life-Support System

Transmitter control logic usually is configured for two states of operation:

- An *operational level*, which requires all of the “life-support” systems to be present before the high-voltage (HV) command is enabled.
- An *overload level*, which removes HV when one or more fault conditions occur.

The cooling system is the primary life-support element in most RF generators. The cooling system should be fully operational before the application of voltages to the tube. Likewise, a cool-down period usually is recommended between the removal of beam and filament voltages and shutdown of the cooling system.

Most microwave power tubes require a high-voltage removal time of less than 100 ms after the occurrence of an overload. If the trip time is longer, damage to the device may result. *Arc detectors* often are installed in the cavities of high-power tubes to sense fault conditions and shut down the high-voltage power supply before damage can be done to the tube. Depending on the circuit parameters, arcs can be sustaining, requiring removal of high voltage to squelch the arc. A number of factors can cause RF arcing, including:

- Overdrive condition
- Mistuning of one or more cavities
- Poor cavity fit (applies to external types only)
- Undercoupling of the output to the load
- Lightning strike at the antenna

- High VSWR

Regardless of the cause, arcing can destroy internal elements or the vacuum seal if drive and/or high voltage are not removed quickly. A lamp usually is included with each arc detector photocell for test purposes.

## 6.9.2 Protection Measures

A microwave power tube must be protected by control devices in the amplifier system. Such devices offer either visual indications or aural alarm warnings, or they actuate interlocks within the system. Figure 6.89 shows a klystron amplifier and the basic components associated with its operation, including metering for each of the power supplies. Other types of microwave power devices use similar protection schemes. Sections of coaxial transmission line, representing essential components, are shown in the figure attached to the RF input and RF output ports of the tube. A single magnetic coil is shown to represent any coil configuration that may exist; its position in the drawing is for convenience only and does not represent its true position in the system.

### Heater Supply

The heater power supply can be either ac or dc. If it is dc, the positive terminal must be connected to the common heater-cathode terminal and the negative terminal to the second heater terminal. The amount of power supplied to the heater is important because it establishes the cathode operating temperature. The temperature must be high enough to provide ample electron emission, but not so high that emission life is jeopardized.

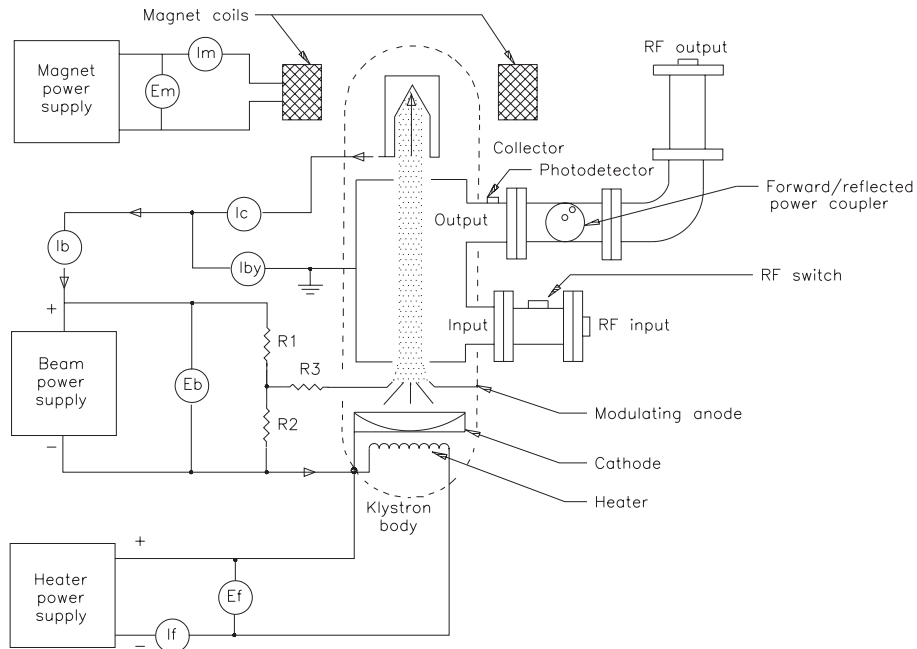
Because the cathode and heater are connected to the negative side of the beam supply, they must be insulated to withstand the full beam potential. This dictates the use of a filament transformer designed specifically for the specific application.

### Beam Supply

The high-voltage beam supply furnishes the dc input power to the microwave device. In a klystron, the positive side of the beam supply is connected to the body and collector. The negative terminal is connected to the common heater-cathode terminal. Never connect the negative terminal of the beam supply to the heater-only terminal because the beam current will then flow through the heater to the cathode and cause premature heater failure. The voltmeter,  $E_b$  in Figure 6.89, measures the beam voltage applied between the cathode and the body of the klystron.

Current meter  $I_c$  measures collector current, typically 95 percent or more of the total device current. Current meter  $I_{by}$  measures body current. An interlock should interrupt the beam supply if the body current exceeds a specified maximum value.

The sum of the body current ( $I_{by}$ ) and collector current ( $I_c$ ) is equal to the beam current ( $I_b$ ), which should stay constant as long as the beam voltage and modulating-anode voltage are held constant.



**Figure 6.89** Protection and metering system for a klystron amplifier.

### Magnet Supply

Electrical connections to the dc magnet supply typically include two meters, one for measuring current through the circuit ( $I_m$  in Figure 6.89), and one for measuring voltage ( $E_m$ ). When a microwave device is installed in its magnet assembly, both parameters should be measured and recorded for future reference. If excessive body current or other unusual symptoms occur, this data will be valuable for system analysis.

Undercurrent protection should be provided to remove beam voltage if the magnetic circuit current falls below a preset value. The interlock also should prevent the beam voltage from being applied if the magnetic circuit is not energized. This scheme, however, will not provide protection if windings of the magnet are short-circuited. Short-circuited conditions can be determined by measuring the normal values of voltage and current and recording them for future reference.

The body-current overload protection should actuate if the magnetic field is reduced for any reason.

## RF Circuits

In [Figure 6.89](#), monitoring devices are shown on the RF input and output of the klystron. These monitors protect the device in case of a failure in the RF output circuit. Two directional couplers and a photodetector are attached to the output of the device. These components and an RF switching device on the input form a protective network against output transmission line mismatch. The RF switch is activated by the photodetector or the reflected power monitor and must be capable of removing RF drive power from the tube in less than 10 ms (typically).

In the RF output circuit, the forward power coupler is used to measure the relative power output of the microwave device. The reflected power coupler measures the RF energy reflected by the output circuit components or antenna. Damaged components or foreign material in the RF line will increase the RF reflected power. The amount of reflected power should be no more than 5 percent of the actual forward RF output power of the tube in most applications. An interlock monitors the reflected power and removes RF drive to the device if the reflected energy reaches an unsafe level. To protect against arcs occurring between the monitor and the output window, a photodetector is placed between the monitor and the window. Light from an arc will trigger the photodetector, which actuates the interlock system to remove RF drive before the window is damaged.

### 6.9.3 Filament Voltage Control

Extending the life of a microwave tube begins with accurate adjustment of filament voltage, as noted in the previous section. The filament should not be operated at a reduced voltage in an effort to extend tube life, as in the case of the thoriated tungsten grid tube. In a microwave tube, reduced filament voltage may cause uneven emission from the surface of the cathode with little or no improvement in cathode life.

Voltage should be applied to the filament for a specified warm-up period before the application of beam current to minimize thermal stress on the cathode/gun structure. However, voltage should not be applied to the filaments for extended periods (typically 2 hours or more) if no beam voltage is present. The net rate of evaporation of emissive material from the cathode surface is greater without beam voltage. Subsequent condensation of material on gun components may lead to voltage standoff problems.

### 6.9.4 Cooling System

The cooling system is vital to any RF generator. In a high-power microwave transmitter, the cooling system may need to dissipate as much as 70 percent of the input ac power in the form of waste heat. For vapor-phase-cooled devices, pure (distilled or demineralized) water must be used. Because the collector is usually only several volts above ground potential, it is generally not necessary to use deionized water. (Cooling considerations for microwave power tubes are discussed in Chapter 8. Cooling system maintenance is examined in Chapter 9.)

### 6.9.5 Reliability Statistics

Determination of the *mean time between failure* (MTBF) of a microwave tube provides valuable information on the operation of a given device in a given installation. The following formulas can be used to predict tube life in operating years, and to estimate the number of replacement tubes that will be needed during the life of an RF generator.

$$Y = \frac{MTBF}{H} \quad (6.4)$$

$$N = \frac{L \times S}{Y} \quad (6.5)$$

$$R = N - S \quad (6.6)$$

Where:

$Y$  = Tube life in operating years

$MTBF$  = Tube mean time between failure (gathered from manufacturer literature or on-site experience)

$H$  = Hours of operation per year (= 365 hours per operating day)

$N$  = Number of tubes needed over the life of the transmitter

$L$  = Anticipated life of the transmitter in years

$S$  = Number of tubes per transmitter

$R$  = Number of replacement tubes needed over the life of the transmitter

### MTTR

The *mean time to repair* (MTTR) of a given piece of RF equipment is an important consideration for any type of facility. MTTR defines the *maintainability* of a system. In the case of a microwave generator, the time required to change a tube is an important factor, especially if standby equipment is not available. The example time-change estimates given previously in this chapter (1 hour for an integral-cavity klystron and 4 to 6 hours for a 60 kW UHF external-cavity tube) assume that no preparation work has been performed on the spare device. Pretuning a tube is one way to shorten the MTTR for an external-cavity device. The spare tube is installed during a maintenance period, and the system is tuned for proper operation. After the positions of all tuning controls are documented, the tube is removed and returned to its storage container, along with the list of tuning control settings. In this way, the external-cavity tube can be placed into service much faster during an emergency. This procedure probably will not result in a tube tuned for optimum performance, but it may provide a level of performance that is acceptable on a temporary basis.

Consideration of MTTR is important for a facility because most microwave tube failure is caused by mechanisms other than reduced cathode emission, which is a *soft*



*failure* that can be anticipated with some degree of accuracy. Catastrophic failures, on the other hand, offer little, if any, warning.

Reliability engineering is discussed in greater detail in Section 9.3.

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