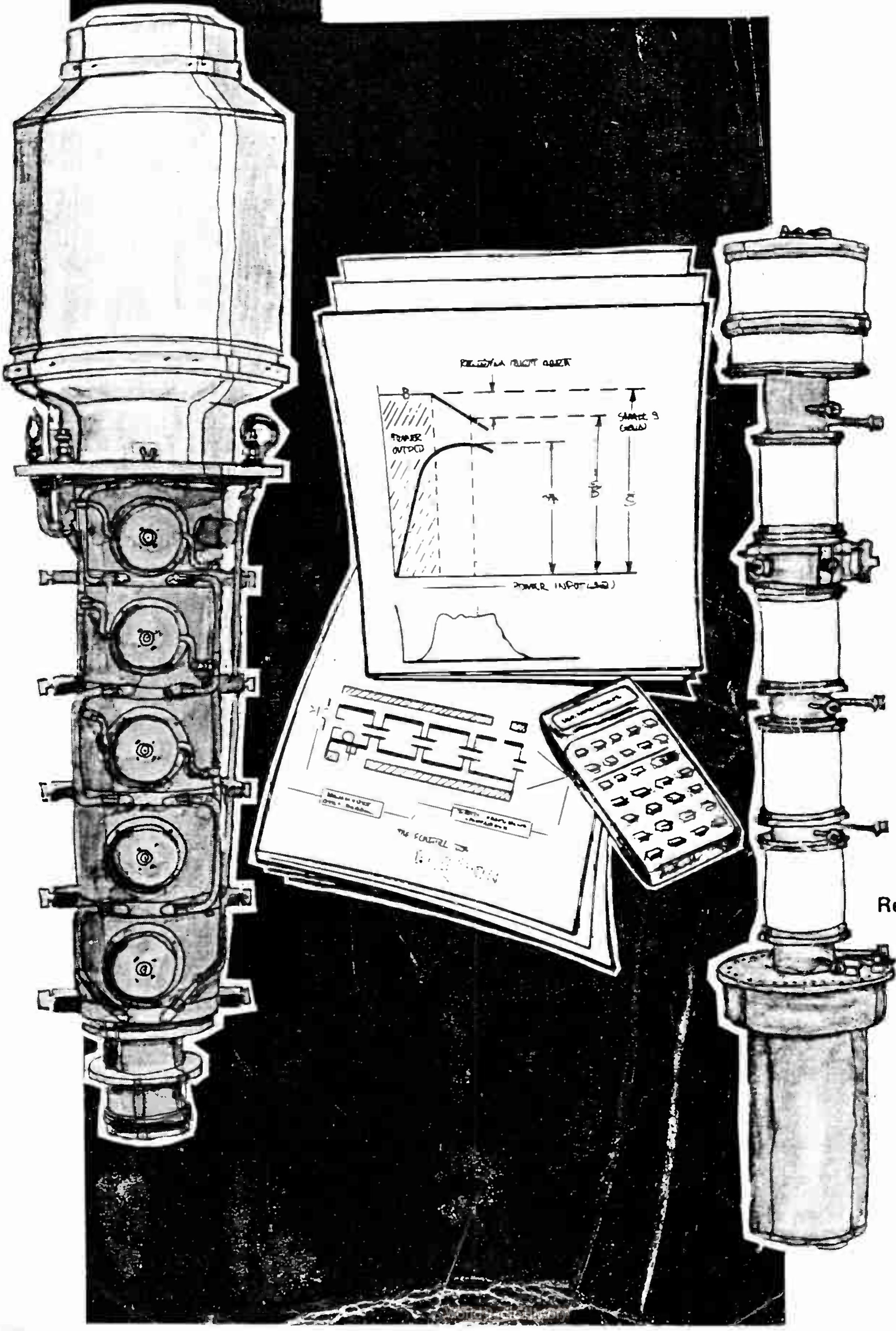
PRACTICAL THEORY AND OPERATION
of UHF-TV KLYSTRONS



by
Reginald D. Perkins

PRACTICAL THEORY AND OPERATION

OF

UHF-TV KLYSTRONS

By:

Reginald D. Perkins

NOVEMBER 1984

Library of Congress Catalog Card Number; 84–90641

R&L TECHNICAL PUBLISHERS
6145 GREENLEAF LANE
FORESTHILL, CALIFORNIA 95631

PREFACE

What more can be said about klystrons that has not already been written by experts in the field of klystron theory and design? There are dozens of textbooks and hundreds of articles that have already been published since the invention of the klystron. They're all filled with theoretical formulas used to explain a particular phenomenon and with many approaches to the design and improvement of the klystron. These are excellent sources if you intend to confine yourself to the design of klystrons.

An area quite often forgotten about is the user of klystrons, technical people who are concerned more with the tube operation and transmission system and, in praticular, users of UHF-TV klystrons. Seeing the need for technical material that bridge the gap between the purely theoretical and a more practical approach to theory and operation, I set out to put together a book with this in mind. I have maintained the unity of a textbook but have strayed from the typical mathematical approach in explaining klystron theory and operation. I have utilized many graphs to explain a phenomenon.

What would be more appropriate in writing this book than to have the people in the TV industry the users of the klystrons, be a part of formulating what they feel they would like to see in a book. Most of the chapters were previewed by various personnel in the UHF-TV industry across the country in order to find out the many areas of concern to the technical personnel using klystrons. In particular, I wish to acknowledge my appreciation to the personnel who were surveyed on various chapters at the Kentucky Educational Television Network. Their responses were a help in formulating a lot of the material. In addition, I wish to thank Varian Associates for the use of the many photographs used throughout this book.

CONTENTS

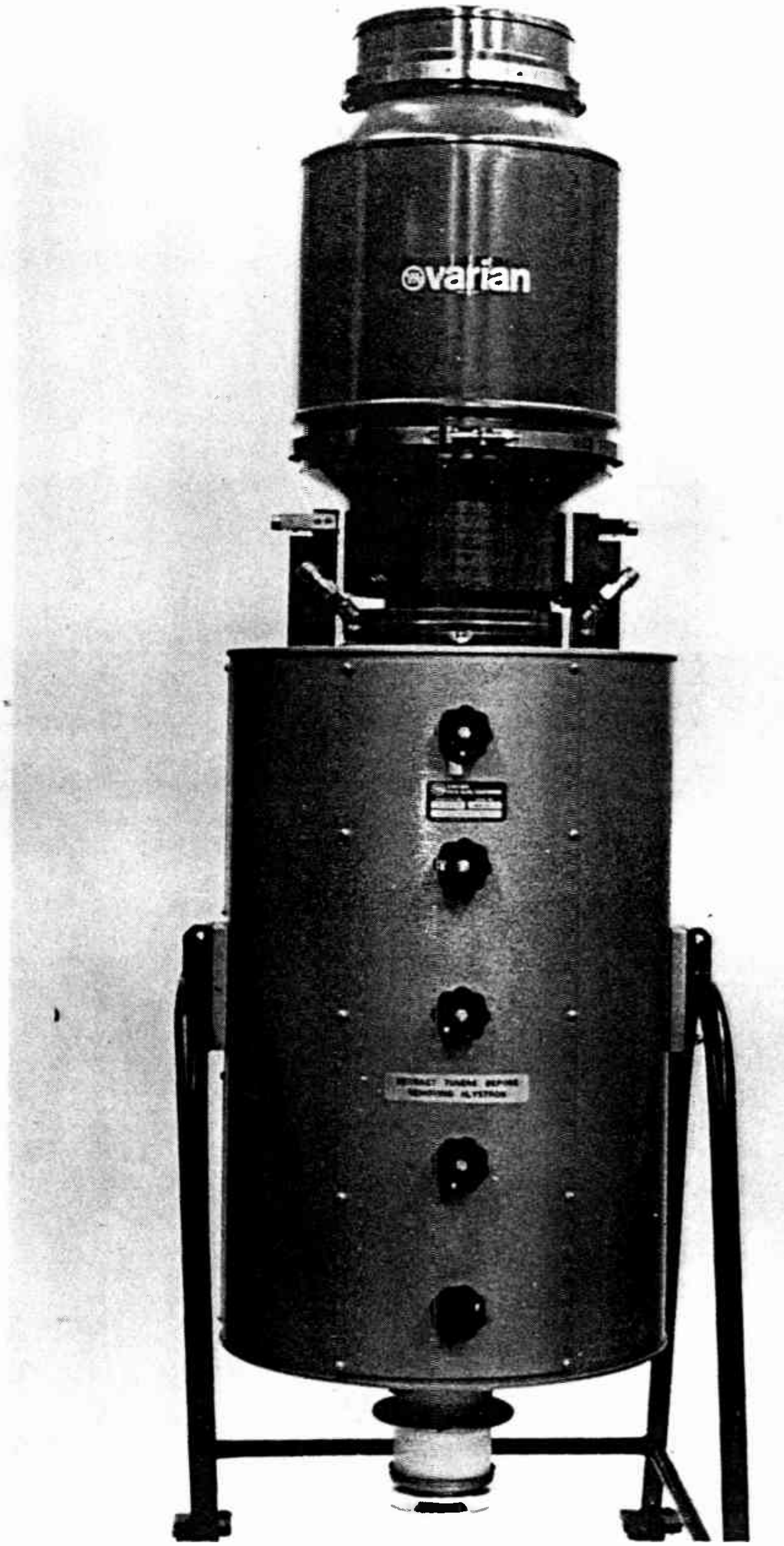


FIGURE 1: VA-953 SERIES UHF-TV KLYSTRON AND ELECTROMAGNET
Photo courtesy of Varian Associates Inc.

INTRODUCTION

This book has been prepared as a general reference for technical personnel in the UHF television industry who are concerned with transmitter/transmission system interface problems.

Most technical personnel associated with UHF television are well versed in the basic television signal generation and analysis but may not be thoroughly familiar with the operation of the equipment which represents one of the most important parts of the transmission system: the video/aural klystron amplifiers. (see Figure 1) One does not need to completely understand the theory of klystrons to operate a UHF-TV transmitter. However, the problems of operating, tuning, and maintenance of a klystron are a very important part of the work expected from a station engineer. A more thorough understanding of the principles of klystrons will always pay off in greater efficiency of the operator. It is anticipated that this text will shed some light on what has often been considered a "shadowy" subject, klystrons.

The klystrons are the funnel through which all video and aural signals must pass on the way to the television viewer. Thus, from a standpoint of good engineering practice and economics, this end-equipment(the klystron) must receive attention at least equal to all the other electronic equipment in the studio.

When instabilities occur in the transmitter/transmission system, by knowing more about how they are caused, we can sometimes take the necessary steps to correct them and even to prevent their recurrence. Technical personnel should be able to recognize the appearance of the more unusual types of transmitter problems or signal impairments that may occur from time to time. Skill in diagnosing the probable general cause of any observed impairment, e.g., a klystron or transmitter problem is a necessary first step in facilitating the location and correction of an operating fault.

Through the years there has been an obvious trend toward remote control operation, and almost all transmitters can be adapted to such operations. The technology of remotely operated transmitters has advanced from simple passive-relay systems to computer-aided systems with ten, twenty, or thirty bits of information.

From a station manager's viewpoint, remote operation provides a saving in operating cost by relieving the technical personnel from being on site at the transmitter all the time. However, if technical personnel are too long absent, the transmitter and klystrons will receive a minimum amount of attention to first echelon maintenance, and usually only what is required by FCC rules or by failure of the equipment will be performed.

There are many pro and con arguments on remote operation by personnel in the TV industry, and I do not wish to slight either side, but do want to impress the importance of personal attention to maintenance, which will pay off in longevity and in trouble-free operation of the klystrons, whether remotely operated or not.

It is surprising that most UHF-TV transmitters are not always chosen because of superior specifications or technical advances. The main considerations in selecting a transmitter are economics, ease of operation, maintainability, and, above all, the ability to get back on the air without delay in the case of failure. However, the problem of operating a television station is too broad a subject to be covered in a single book. I have selected areas which I feel are important and representative of a need to understand the theory and operation of UHF-TV klystrons: how they are built, how they work, their maintenance, and their operating characteristics relating to TV signals.

Typical of the many UHF-TV installations is pictured in Figure 2, showing engineering personnel performing one of the many adjustments and checks necessary to maintain a UHF-TV transmitter installation. Figure 3 pictures the multi-antenna tower used at Mt. Sutro, California.

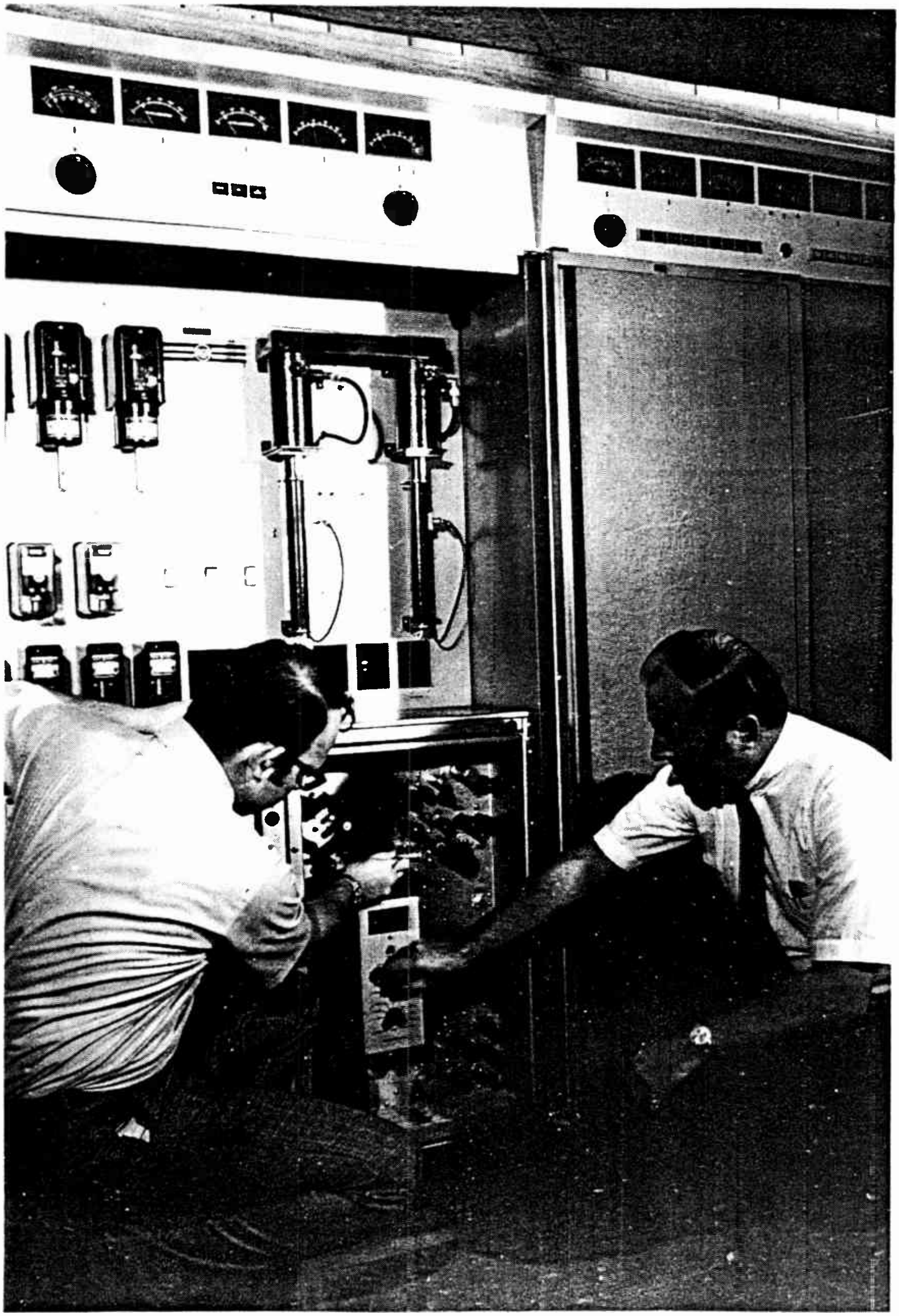


FIGURE 2: UHF-TV TRANSMITTER INSTALLATION
Photo courtesy of Kentucky Educational Television

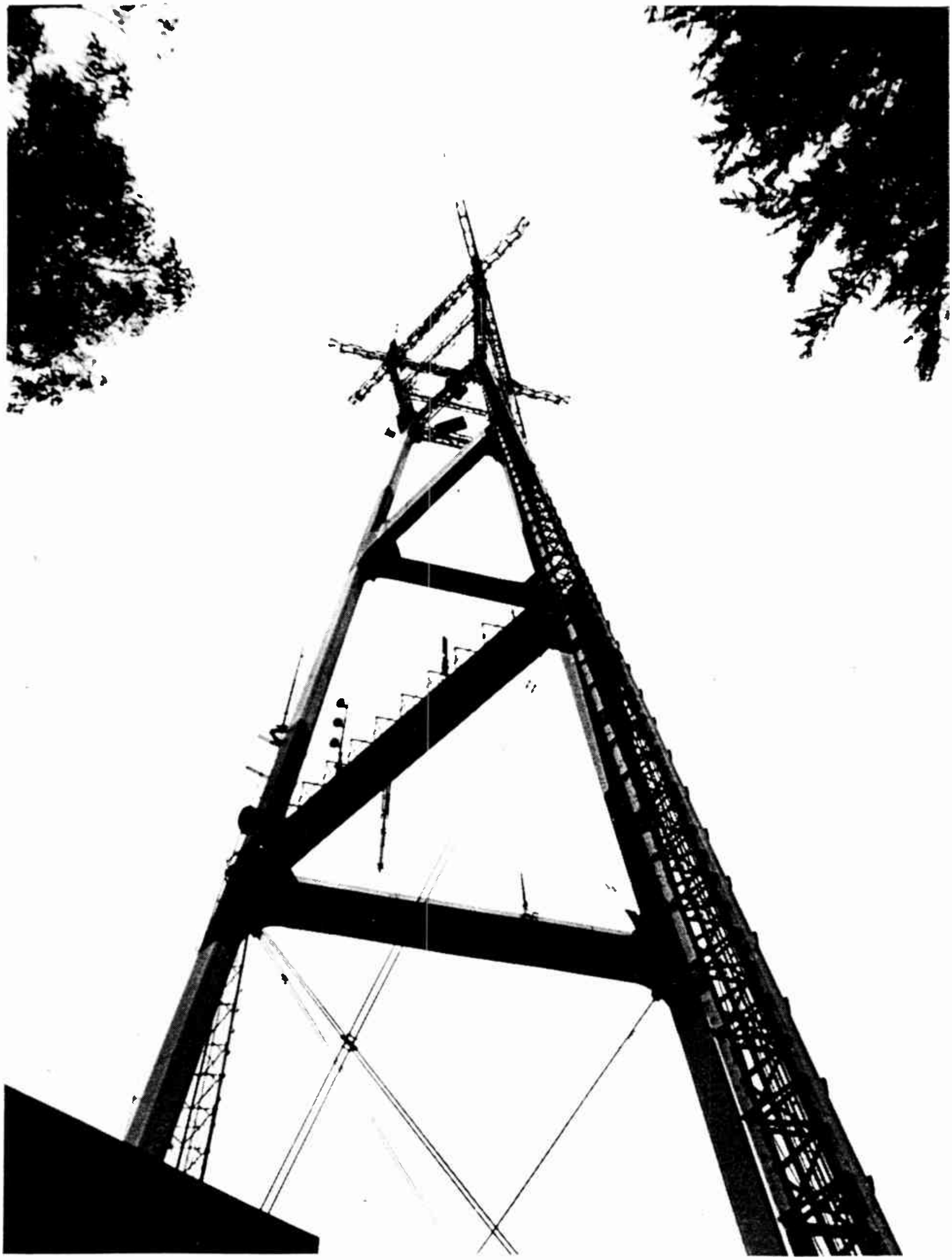


FIGURE 3: UHF-TV AND FM TRANSMITTING ANTENNA TOWER
MT. SUTRO, SAN FRANCISCO, CALIFORNIA
Photo courtesy of Varian Associates Inc.

1. THE KLYSTRON AMPLIFIER AND UHF

1.1 General

A great deal has been written about klystrons through the years, but very little practical information has been written about the operation of the UHF-TV klystron specifically.

This presentation is primarily for those engineers and technicians in the television broadcast industry who are confronted with operating and maintaining a high-power UHF-TV transmitter using klystrons, but who may not be thoroughly familiar with current, basic klystron technology, theory, or operations relating to UHF-TV.

It is assumed that the reader is familiar with general electronic theory and operation of rf amplifiers such as triodes, which will be of help in the discussion of and analogy to klystron operation. The presentation will be a simplified non-mathematical approach, and should give the reader a better understanding of what is going on in the tubes, and the reasons behind some of the operating instructions which are presented in a typical manufacturer's Instruction Manual. It should also be understood that the discussions in this text are not meant to circumvent specific instructions of any manufacturer of TV systems or components.

There are two basic types of klystrons, each one easily identifiable by comparison.

(1) Reflex (oscillator)

(2) Multi-cavity (amplifier or oscillator)

The reflex klystron is essentially a small, low-powered, single-cavity microwave device which has been utilized in many microwave systems that involve television transmissions.

The multi-cavity klystron, as the name implies, has more than one cavity and could have as many as 6 or 7 cavities, and the multi-cavity oscillator klystron typically has 2 cavities. However, this presentation will be restricted to only 4 and 5 cavity amplifiers.

One cannot discuss UHF-TV klystrons without at least differentiating between the internal and external cavity concept of operation. The theory is the same for both concepts, and the slight differences in operation will be explained in detail in the section on operating characteristics. The klystrons pictured in Figures 4 and 5 are two of the many varieties that are used in UHF-TV transmitters. The tube pictured in Figure 4 is one of the internal cavity types (4 cavities). Figure 5 shows an external cavity tube and Figure 6 shows the removable external cavities attached to the tube. Familiarize yourself with the basic components listed for each tube type, as they will be referred to in the various sections that follow.

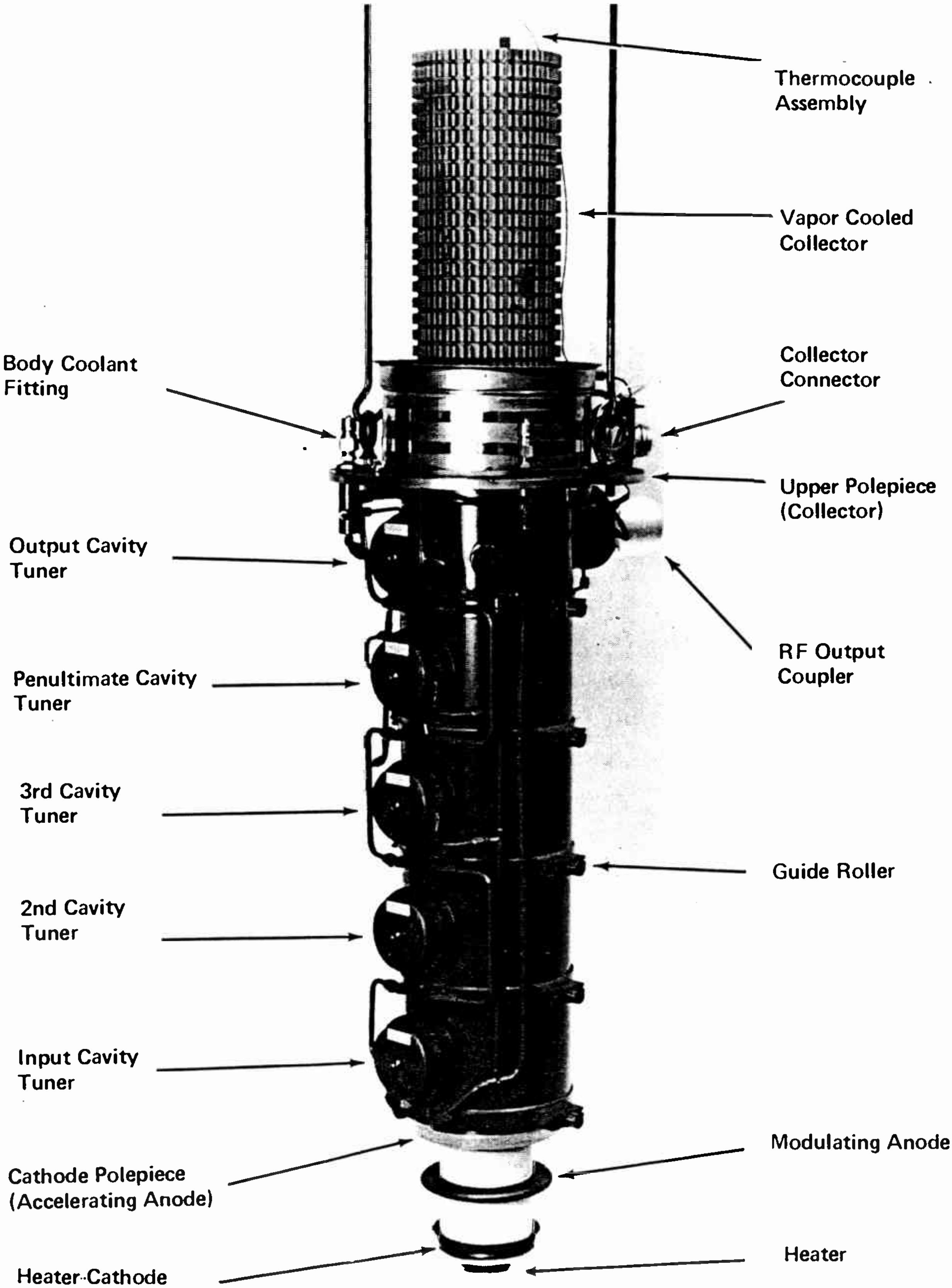


FIGURE 4: VA-953, SERIES, INTERNAL CAVITY UHF-TV KLYSTRON
Photo courtesy of Varian Associates, Inc.

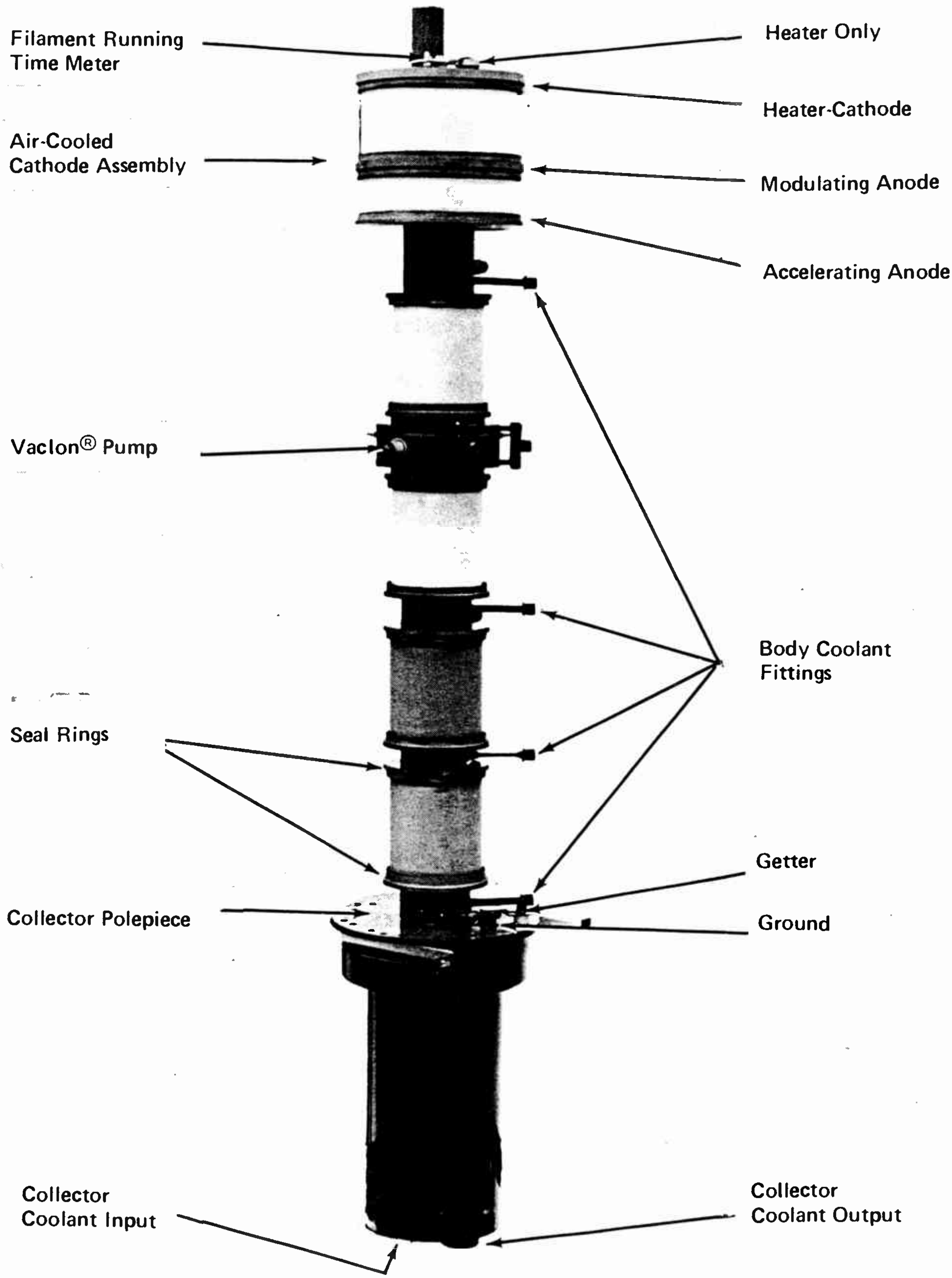


FIGURE 5: 4KM150, EXTERNAL CAVITY UHF-TV KLYSTRON
Photo courtesy of Varian Associates Inc.

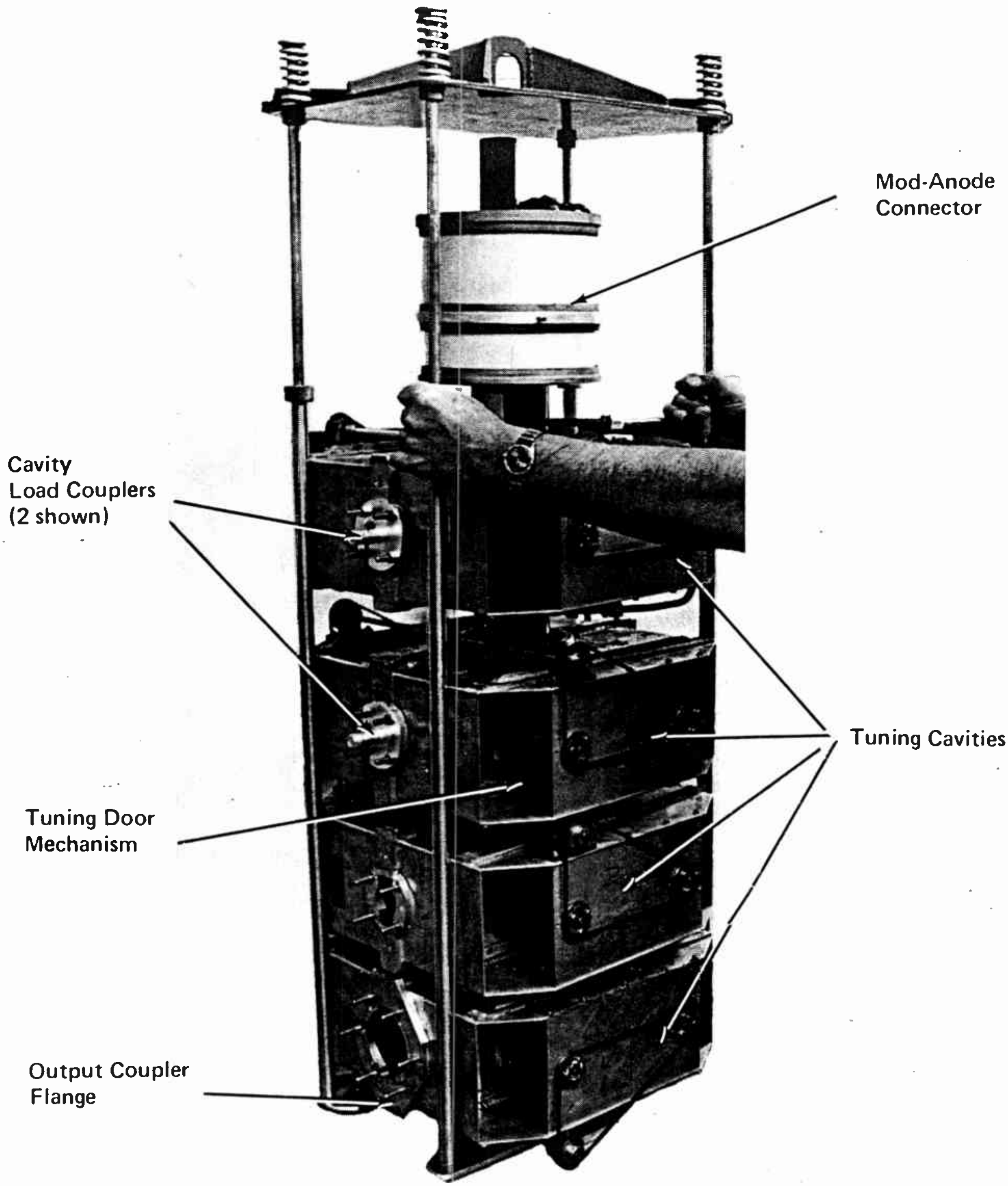


FIGURE 6: 4KM150 KLYSTRON AND EXTERNAL TUNING CAVITIES
Photo courtesy of Varian Associates Inc.

1.2 Why Klystrons?

Conventional vacuum tubes that are used in low-frequency radio broadcast transmitters are not efficient sources of energy at UHF frequencies, and the very reason why they won't work efficiently is the reason why klystrons will. (There are exceptions to this, one being specially designed triode or tetrodes which have been built to operate at UHF and microwave frequencies using special resonant cavities in place of the conventional L/C circuits, but these tubes suffer from limitations in power.)

Obviously there are differences between the triode and klystron vacuum tubes and these differences are enough so the klystron will amplify at UHF and microwave frequencies, while most conventional tubes will not. In fact, the klystron amplification principle can be readily explained by analogy to a simple triode rf amplifier. The triode consists of three(3) elements: a cathode which emits a stream of electrons, a grid that is in the path of the stream of electrons and a plate that attracts the electrons and catches them after they pass through the grid.

The application of the triode and other vacuum tubes that contain three or more electrodes is based on a separation of the three electrode circuits into three systems: the input, output, and cathode (see Figure 7). The input circuit contains circuit elements between the control grid as one boundary and the grounded common voltage reference point as the other boundary. The output circuit includes all circuit elements between the plate and the common voltage reference point, and last, the cathode circuit includes all the elements in the system between the emitter proper and the common voltage reference point.

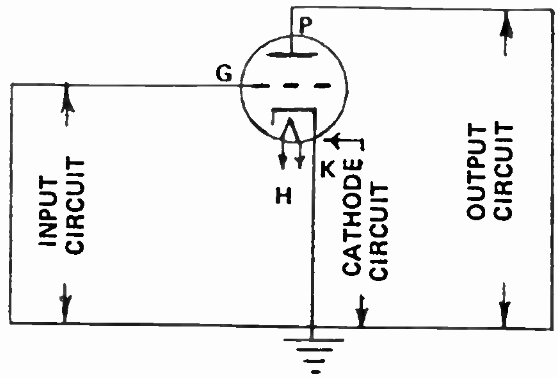


FIGURE 7 : BASIC INPUT, CATHODE AND OUTPUT CIRCUIT OF TRIODE

In addition, the circuit division is based on the voltages applied to each electrode which is also related to the paths of signal currents that flow in the tube circuits, even though the different voltage sources have been omitted for explanation purposes.

Now, let us review the operations of a triode amplifier with resonant circuits at both the input and output of the tubes (see Figure 8). These resonant circuits very simply restrict the bandwidth of the amplifier and increase the gain.

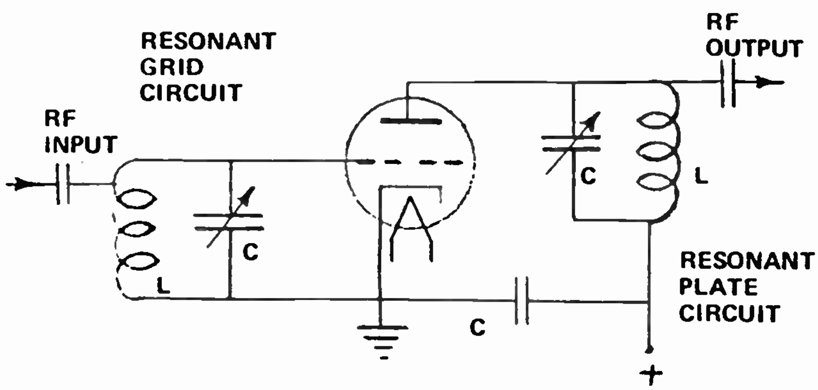


FIGURE 8 : TRIODE TUBE RF AMPLIFIER

Resonant circuits[1] are quite often thought of as being two or more combinations of inductance and capacitance tuned to the same frequency. Opposition to the flow of current in such a circuit is called resistance. When direct current is flowing in a circuit, the higher the resistance and the less current for a given voltage and vice-versa.

When alternating current is flowing in a circuit, resistance is not the sole factor to be considered. We must take into consideration two additional factors: capacitive reactance and inductive reactance. Capacitive reactance indicates the ability of a capacitor to store energy in the form of an electric field. Inductive reactance applies to the ability of an inductor to store energy in the form of a magnetic field.

When the effects of a capacitive and inductive reactance are canceled out, as in the case when one equals the other, the condition of resonance is obtained, and only the resistance of the circuit (which is usually very low) remains to affect the flow of current; thus a circuit is said to be tuned to the frequency of an ac voltage. When a circuit is detuned, it simply means that the circuit is no longer at the resonant frequency.

In other words, resonance is the condition existing when the resistance of an ac circuit is the main factor affecting the current flow and all other factors (at that particular ac frequency) have been canceled out. Therefore, with the flow of current, there is amplification.

The total current flow in a tube such as a triode is determined by the applied plate voltage and the voltage on the grid. The velocity and transit time of these electrons depends entirely upon the positive plate voltage, while the grid voltage will vary only the quantity or density of the electrons traveling from the cathode through the grid toward the plate.

[1]This is a very basic definition for the condition of resonance. It is important that we define resonance now for future discussions on klystron rf circuits.

The grid thus acts as a valve, opening or closing the passage of electrons (such as the action of a water faucet) according to the voltage applied to it (see Figure 9).

The plate voltage is normally positive and the grid is normally negative. If the grid is made more negative, it tends to reduce the flow of electrons (Figure 9B). If the grid is made less negative, the flow of electrons is increased (Figure 9A). In other words, varying the grid's "negative potential" (called bias) varies the plate current. It is possible to make the grid so negative that no electrons will reach the plate and no plate current will flow (Figure 9C).

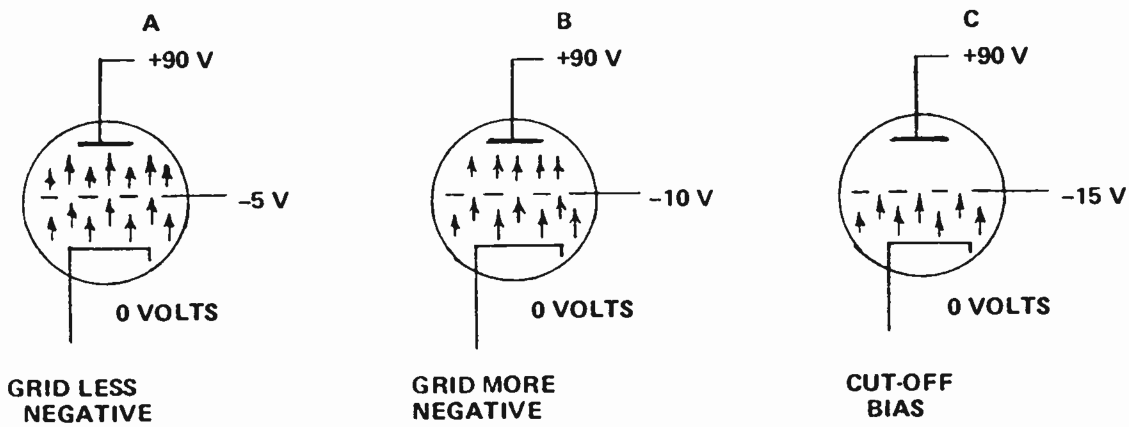


FIGURE 9 : CONTROL OF ELECTRON FLOW IN TRIODE BY GRID VOLTAGE

The rf input signal comes to the grid as a weak alternating current, oscillating at the rf frequency. The oscillating voltage thus applied to the grid modulates the flow of electrons that travel across the tube at the rf frequency. The electron stream then delivers, at the plate, an alternating current which reproduces the weak signal on the grid with amplification. This alternating current at the plate flows through the resonant plate circuit and excites alternating voltages across it; these alternating voltages constitute the rf output from the amplifier.

The time it takes an electron to cross the tube from the cathode to the plate is in the order of a billionth of a second. This transit time is short when compared to the cycle of a low-frequency radio wave (around a millionth of a second). Thus the quantity of electrons is controlled by the voltage on the grid at a moment of the rf cycle. The flow of electrons, therefore, can follow the voltage fluctuations on the grid.

However, at high frequencies, e.g., UHF and above, the voltage swing on the grid oscillates very rapidly, and the grid cycle is so short that the grid may go through several complete oscillations during the time an electron takes to travel across a tube. In other words, the grid voltage changes too fast and produces unstable operation. If the frequency is high enough, oscillations or amplification will cease. This effect is the result of transit time of the electrons.

Through the years, tube designers have attempted to overcome the problem of transit time in the triode or conventional vacuum tubes by various means. This is accomplished by two basic methods: increasing the plate voltage and by reducing the spacing between the electrodes. This approach has its limitations: increasing the anode (plate) potential introduces problems of dissipating the added power in the anode, and reducing the spacing of the elements increases the inter-electrode capacitance. Consequently, most ordinary gridded vacuum tubes have an upper frequency limit where they are either very inefficient, consistent with high power and bandwidth, or cease to operate entirely. Klystrons, on the other hand, have internal electrode spacings at least one order of magnitude greater than the triode or conventional vacuum tube at a given frequency and power level.

The klystron uses the very thing that defeats the triode, transit time of the electron, for the essential part of its operation. An rf voltage is used to "modulate" the velocity of the electrons. In other words, velocity modulation means that a control voltage, developed by the applied rf voltage, speeds up or slows down the electron stream into bunches rather than limiting or increasing the number of electrons as it does with density modulation in a triode. Figure 10 illustrates a simplified klystron circuit showing a low level signal applied to the input cavity, bunching of the beam and the amplified signal at the output cavity.

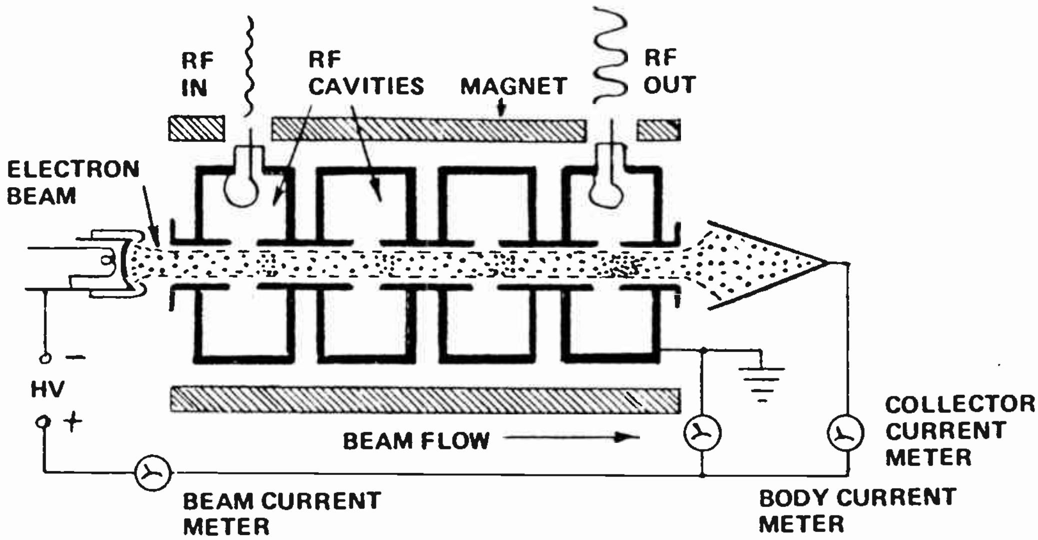


FIGURE 10: BASIC KLYSTRON DIAGRAM

The amplifying process takes place as a result of interaction between the resonant cavities and the electron beam. The voltage developed by the rf input signal in the first resonant cavity is imposed on the beam so that some of the electrons are accelerated during one polarity of the rf signal. During the alternate polarity, other electrons are slowed down. The bunches are strengthened, or made more dense by the intermediate cavities until the bunches of electrons pass through the last cavity gap when they are at their greatest density. As they pass through the output cavity, energy in the beam is transferred to the cavity, coupled out of the cavity,and thus to the load or antenna as rf power.

In summarizing conventional tubes vs klystrons, the conventional tubes (e.g., triodes or tetrodes) have the following disadvantages. The cathode and grid are a definite part of the input rf circuit. In a similar manner, the output rf circuit is closely associated with the plate and grid of the tube. Consequently,the cathode and plate designs must be compromised from the standpoint of good rf design and electron emissions and power dissipating requirements. Grids are necessary, but are delicate and difficult to cool and they intercept electron current and carry rf currents.

Conversely, the klystron electron gun can be designed for one purpose only, and that is to provide an electron beam. The rf circuits and collector also are designed for one purpose only. The purpose of the rf circuit is to transfer radio frequency energy to and from the beam, and the purpose of the collector is to dissipate the spent electrons.

2. KLYSTRONS AMPLIFIER FUNDAMENTALS

2.1 What is a Klystron ?

The multi-cavity klystron is essentially a linear, narrow band amplifier (typically 1 to 2%), for amplifying signals at UHF and microwave frequencies. Bandwidth in this case is defined as that percentage of bandwidth relative to the center frequency of operation and measured to the 3dB points of power, e.g., at 600 MHz a 2% bandwidth is equal to 12 MHz, and a 40 MHz bandwidth at 4 GHz would be equal to 1%.

The klystron amplifier also contains three (3) basic sections similar to the triode: an electron gun, an rf section,(interaction section) and a collector. The multicavity klystron is illustrated schematically as shown in Figure 11.

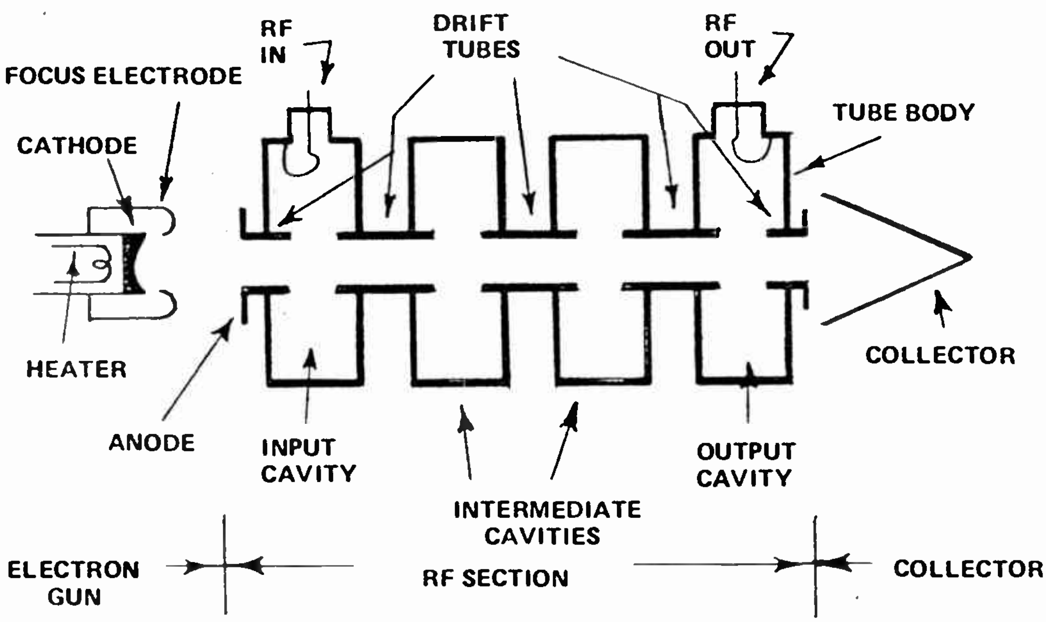


FIGURE 11: PRINCIPLE ELEMENTS OF A KLYSTRON

In this and other chapters the material will cover the basic fundamentals of klystron amplifiers in order to establish a good practical foundation of theory before discussing specific UHF TV klystrons. The major difference in the klystron vs the triode is the rf section which uses resonant re-entrant cavities in place of the usual lumped L/C circuit to develop the controlling voltage for the electron flow.

The rf section (also called interaction section), where the amplification occurs, contains a number of re-entrant cavities (see Chapter 5.0) and field free drift spaces where electric fields are developed through interaction with an electron beam. Re-entrant cavities differ from the familiar coaxial cavity in that they are closed off on both ends with capacity loading (see rf section). The electron beam passes through the cavity gaps in each of the resonators (cavities) and through cylindrical metal tubes called "drift tubes" (drift spaces).

The applied high voltage between the cathode and body affects directly only the initial velocity with which the electrons travel. The first resonant cavity encountered by an electron in the beam is excited by the microwave signal to be amplified and an alternating voltage of signal frequency is developed across the drift tube gaps. This alternating voltage "modulates" the velocity of the electrons so that as they travel through the tube, they sort themselves into groups and arrive at their destination (see Figure 12) in very tight bunches and are thus dissipated by the collector. These bunches deliver an oscillating current to the output cavity of the klystron and are coupled out of the cavity as amplified rf power. A simple analogy of the bunching would be like a stream of cars on a freeway, traveling at different speeds. The faster cars would overtake the slower ones and tend to cause periodic bunches along the freeway.

Figure 12 illustrates a basic multi-cavity klystron with its electromagnet, showing the beam and bunching. The beam is represented here as a linear beam, not as a "boloney sausage" which often causes confusion in understanding the bunching action. There is scalloping of the bunched beam due to stray electrons or debunching

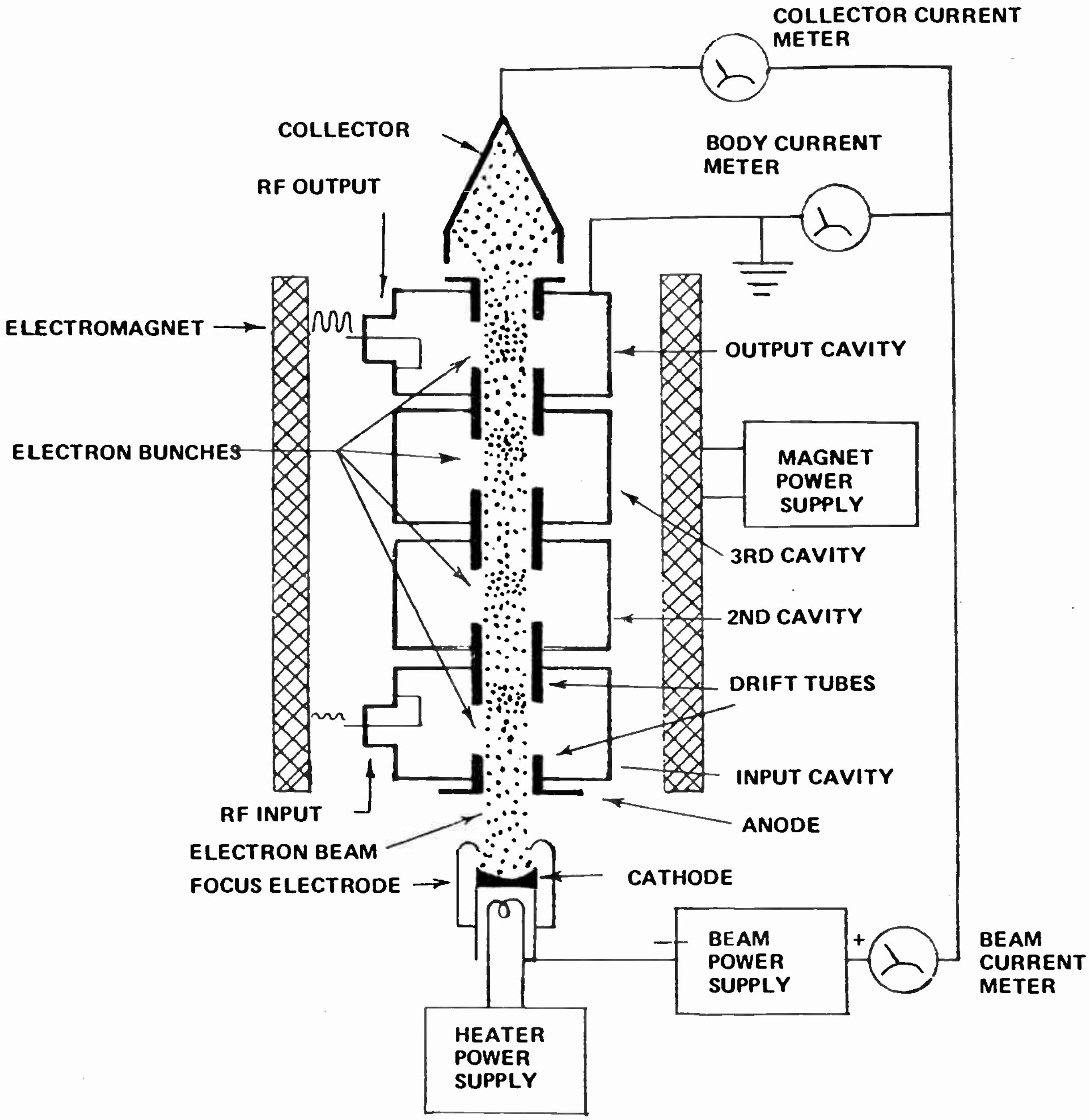


FIGURE 12: BASIC KLYSTRON AND POWER SUPPLY CONNECTIONS

under some conditions of drive, however, this will be covered in detail in the section on Bunching Action. The control anode (modulating-anode) commonly associated with most UHF-TV variety klystrons has also been eliminated at this time in order to discuss only the basic operation of klystrons. However, the use of the modulating-anode will be covered at the appropriate time later in the text. Consequently, the use of the word anode or accelerating anode as it is sometimes referred to, should not be confused with the term "modulating-anode"; they are separate and distinct elements in the tube.

Above all, the bunching phenomenon and interaction is a very important part of the klystron fundamentals and is essential to the complete understanding of its operation; therefore, each section of the tube will be covered separately in greater detail in the next few chapters.

3. ELECTRON GUNS

(Cathode Operation and Electron Flow)

The choice of a good electron gun design is essential to the operation of a klystron or any tube for that matter. The gun must provide the source of free electrons and generate an electron stream that is formed into a beam that will travel the entire length of the tube.

Electron guns are designed in a variety of sizes and shapes depending on the application and the basic design concept of the tube; consequently, each klystron uses the design best suited for it. This should be evident by observing just the external view of the two electron gun assemblies pictured in Figures 4 and 5 in Chapter 1. Both of these electron guns are constructed with a modulating-anode as the controlling element but both have widely different construction and beam optics. Several variations of electron guns in general use for controlling the electron flow in klystrons are: cathode, mod-anode, grid (nonintercepting and intercepting) and shadow grid control which are illustrated schematically in Figure 13.

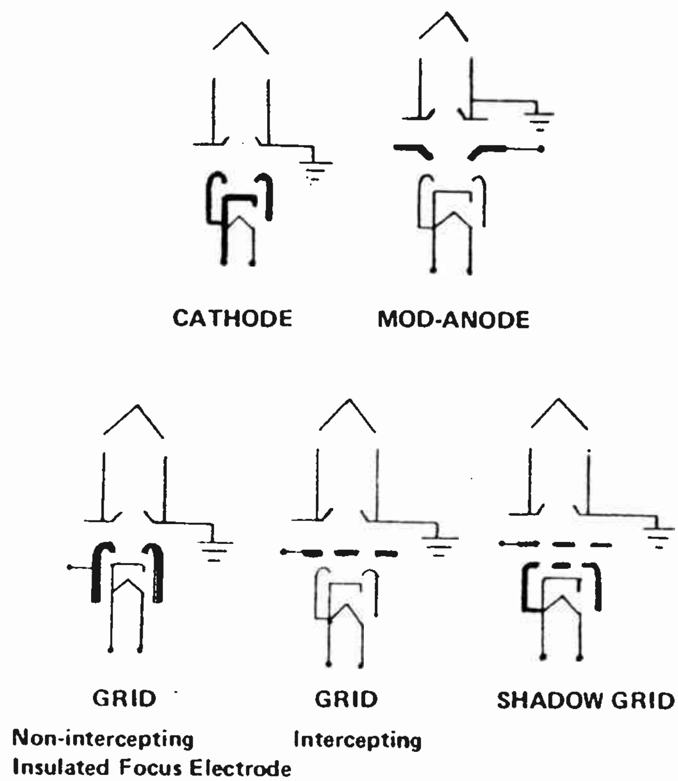


FIGURE 13: ELECTRON BEAM CONTROL METHODS

The different electron guns shown in Figure 13 are for information purposes only, as the discussion in this text will cover two types: the cathode and mod-anode control electron guns.

The most basic of all beam control methods shown in Figure 13 is the cathode control, which will be the basis to start our discussion. Figure 14 illustrates a typical cathode-control electron gun, containing a heater, cathode (emitting element), a beam-forming element, and an anode. The anode that is part of the body is not an integral part of an electron gun assembly. However, it is included here as a necessary part of the discussion, which will be pointed out later. Any detail on support construction has also been eliminated for reasons of simplicity. This part of the text will cover heaters, different types of cathodes, electron emission, and, finally, the complete electron gun.

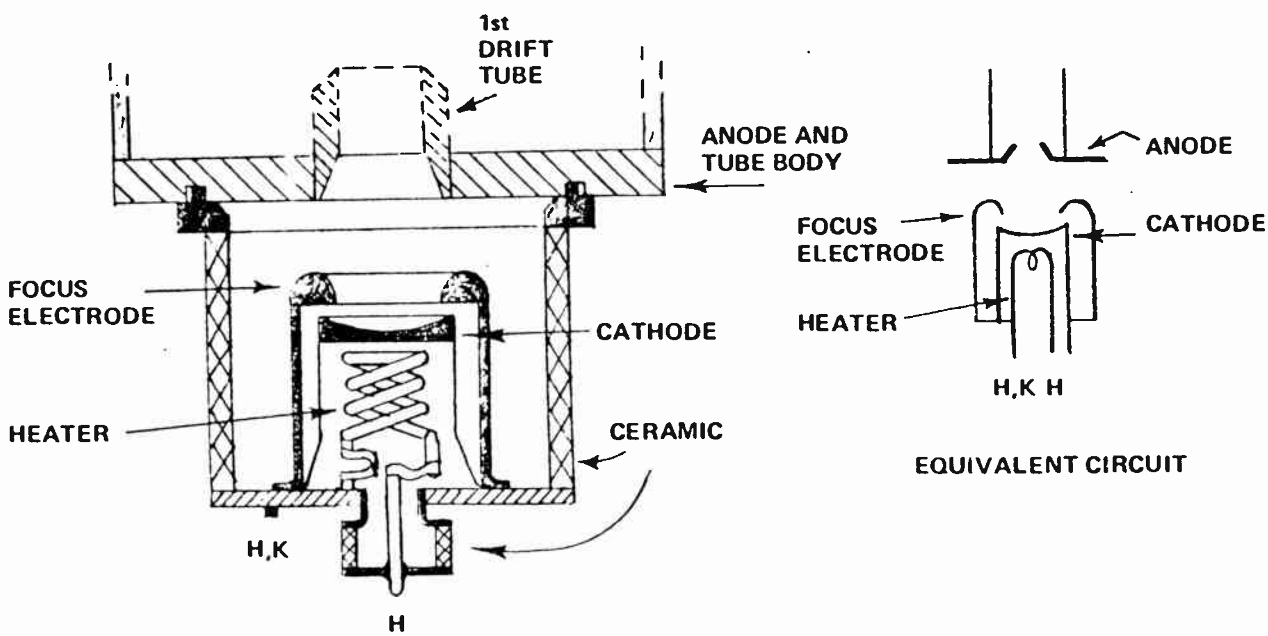


FIGURE 14: BASIC ELECTRON GUN ASSEMBLY

In order to eliminate any possibility of confusion between the conventional understanding of cathode and filament types of emitters, their physical differences are taken for granted; but it is necessary to select one or the other term for easiest reference to emitters. Accordingly, the word "heater" will be used to denote the element that supplies the heat to the electron emitter, and the word "cathode" will denote the electron emitter in all cases. Furthermore, the discussion will be confined to the indirectly heated cathode. Quite often the term "gun ceramic" has also been used to describe the electron gun assembly. This is incorrect. A gun ceramic is a cylindrical piece of ceramic that is part of the vacuum envelope only. The term "electron gun or cathode" is the correct terminology, and will be used throughout this text.

3.1 Heaters

Electron emission is essential to the operation of all electron tubes including klystrons. Electron emission can be accomplished by four methods; thermionic, secondary emission, photoelectric emission and cold-cathode emission, the most important of which is thermionic emission. In thermionic emission, heat is the form of energy that is used to liberate electrons from the emitting substance. A heater, similar to the one shown in Figure 14 is used to heat the emitting material of a cathode to the required operating temperature.

In order for heaters to produce high temperatures and to withstand normal operating conditions, they must be constructed out of materials that have a high electrical resistance and a high melting temperature. Tungsten is a material that has both of these properties (or alloys of tungsten and molybdenum). Pure tungsten possesses the greatest durability and is therefore used in vacuum tubes which may be subjected to heavy overloads.

The operating temperature of tungsten heaters according to the application may vary from approximately 1200° C (2192° F) to 1600° C (2912° F) while the emitting surface of the cathode may only be operating somewhere around 800° C (1472° F) to 1200° C (2192° F). Please note that we are discussing indirectly heater cathodes and there is a difference between the heater temperature and the temperature of the emitting (cathode) material. Conversely, tungsten-filament emitters have an operating temperature range from 2000° C (3632° F) to 3000° C (5432° F) according to design and application. Actually, most of these are operated at approximately 2200° C (3992° F) to 2500° C (4532° F) and glow with a white light.

> Note: Most electron guns on klystrons are built with indirectly heated cathodes and ceramic insulating material for the vacuum seal (similar to Figure 14) and it is difficult to see a glow of the heater through the ceramic. If there is a noticeable glow in a well-lighted room, the heater is probably operating at too high a temperature and it would be advisable to investigate the heater circuit for correct operating conditions before damage results to the heater.

When tungsten is operated at elevated temperatures, such as with a heater filament or cathode substance, there is a gradual evaporation of the metal due to heating. It becomes thinner with time and eventually one part of the heater may become too weak to carry current and burn out. The evaporation of thoriated-tungsten is also like that of pure tungsten; consequently, longest life is attained by keeping the voltage constant across the heater and allowing the current to adjust itself in accordance with the changes in heater resistance as the wire becomes thinner.

In actual tube operation, this approach is not always practiced; quite often heater current is set and the voltage ignored. Changes in resistance of the heater circuit may not all be due to the heater evaporation, but are high-resistance connections external from the tube which cause a resultant drop in voltage at the heater terminals.

As a general rule, it has been customary to refer to the end of life of tungsten heaters to the reduction in diameter by evaporation when the quantity of metal reaches approximately 6% to 10% of the original diameter. As an example, if a heater were operating at 20A and had 1V drop per centimeter of wire for a given diameter of wire and length, a change of approximately 10% of the wire diameter at the same voltage drop would give a heater current of approximately 18A. In order to maintain the 20A of heater current with the reduced wire diameter, the voltage drop per centimeter of wire would have to be increased to approximately 1.25V, by increasing the overall operating heater voltage. These theoretical values are presented in simplified manner, and any final decision as to the correct operating point should always be made in consultation with the manufacturer.

However, one need not be excessively concerned about tungsten evaporation, as heaters are generally designed to greatly exceed the normal life expectancy of the emitting (cathode) element under normal operating conditions. Burn-out of a heater is most likely to occur for other reasons, such as heavy overloads in the heater/cathode circuit or by voltage transient (see section on impregnated cathodes).

There are numerous forms of heater packages that can be used in electron tubes: e.g., flat, spiral, radiation and encapsulated (potted) heaters. See Figure 15. Mechanically they are obviously different, but the basic operation is similar, except for slight differences in operating temperatures. The choice of heater design is dictated by the physical design of the klystron, its application, and, lastly, by engineering choice.

The flat heater shown in Figure 15A and the spiral heater of Figure 15B are generally called radiation heaters. They are both normally wound in the bi-filar method. These types of heaters are typically used to heat emitting materials that require operating temperatures below 1000° C (1832° F). The heat radiation from the heater of Figure 15A is mostly up or down, thus a much shorter heater package may be used. In Figure 15B the heat radiation is mostly to the sides, thus a good deal of the heat transfer is to the side-support shield of the cathode.

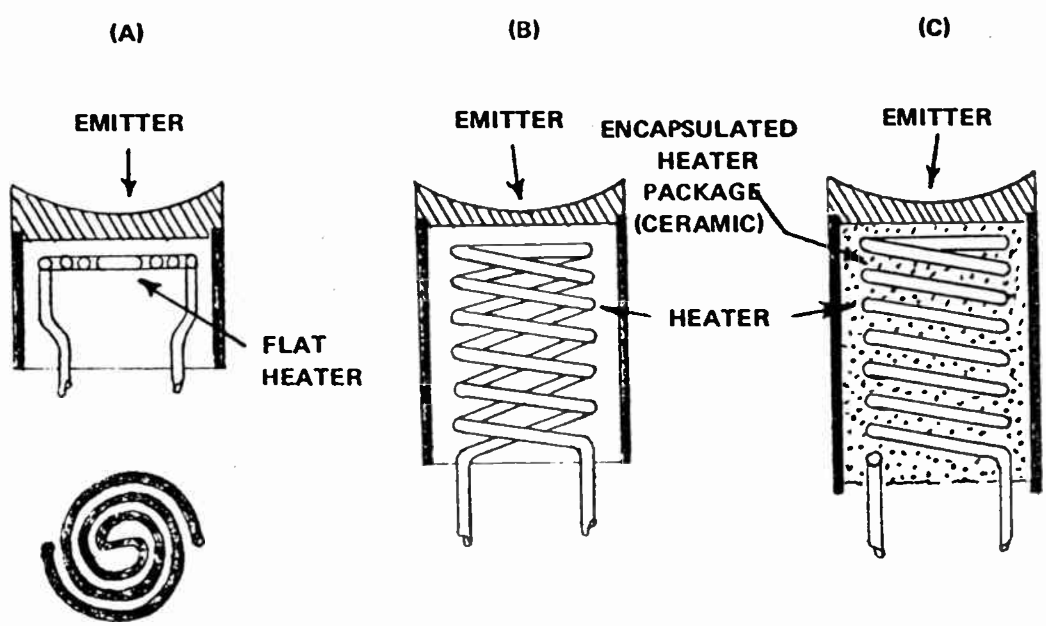


FIGURE 15: TYPES OF HEATER PACKAGES

These two types of heaters are formed of pure, uncoated tungsten wire; they are self-supporting and generally require greater spacing between the wire turns and other parts of the assembly in order to maintain their relative position in the structure. Generally, this is not the most efficient method of heat transfer, thus the heater must operate 500 to 800° C (932 to 1472° F) above the emitting material.

Figure 16 pictures two flat, spiral heaters that are used in different UHF-TV klystrons. The smaller heater is used in the internal cavity klystron electron gun and the larger one is used in the external cavity klystrons electron gun that are shown in Figures 4 and 5 of Chapter 1. The larger heater will not necessarily operate longer than the smaller heater. These particular heaters are used in two separate electron gun designs. The heater voltages are different and the electron guns also have different beam optics and operating potentials. It is function, not longevity that determines heater size.

Both of these types can be made more efficient by the use of heat radiation shields and by an insulating material (alumina) that is applied to the heater wire before assembly into the heater package. The alumina-coated heater is fired at a high temperature in a furnace until the alumina coating hardens into a protective cover around the wire. With the insulating coating, closer spacing can be achieved between the heater turns, emitting surface and general structure. The alumina may also be used to hold the heater in contact with the bottom of the emitting surface, thus becoming a radiation/conduction heater. The heat shields may be of either ceramic (for additional insulation) or metal. With this improved heat transfer capability, such heaters may be used to heat emitting materials requiring temperatures of 900° C (1652° F) to 1100° C (2012° F) The higher temperature is possible providing the size of the emitting surface is not too large. Even with the more efficient transfer of heat, the temperature difference between the heater and emitting surface can be as much as 400° C (752° F) to 500° C (932° F).

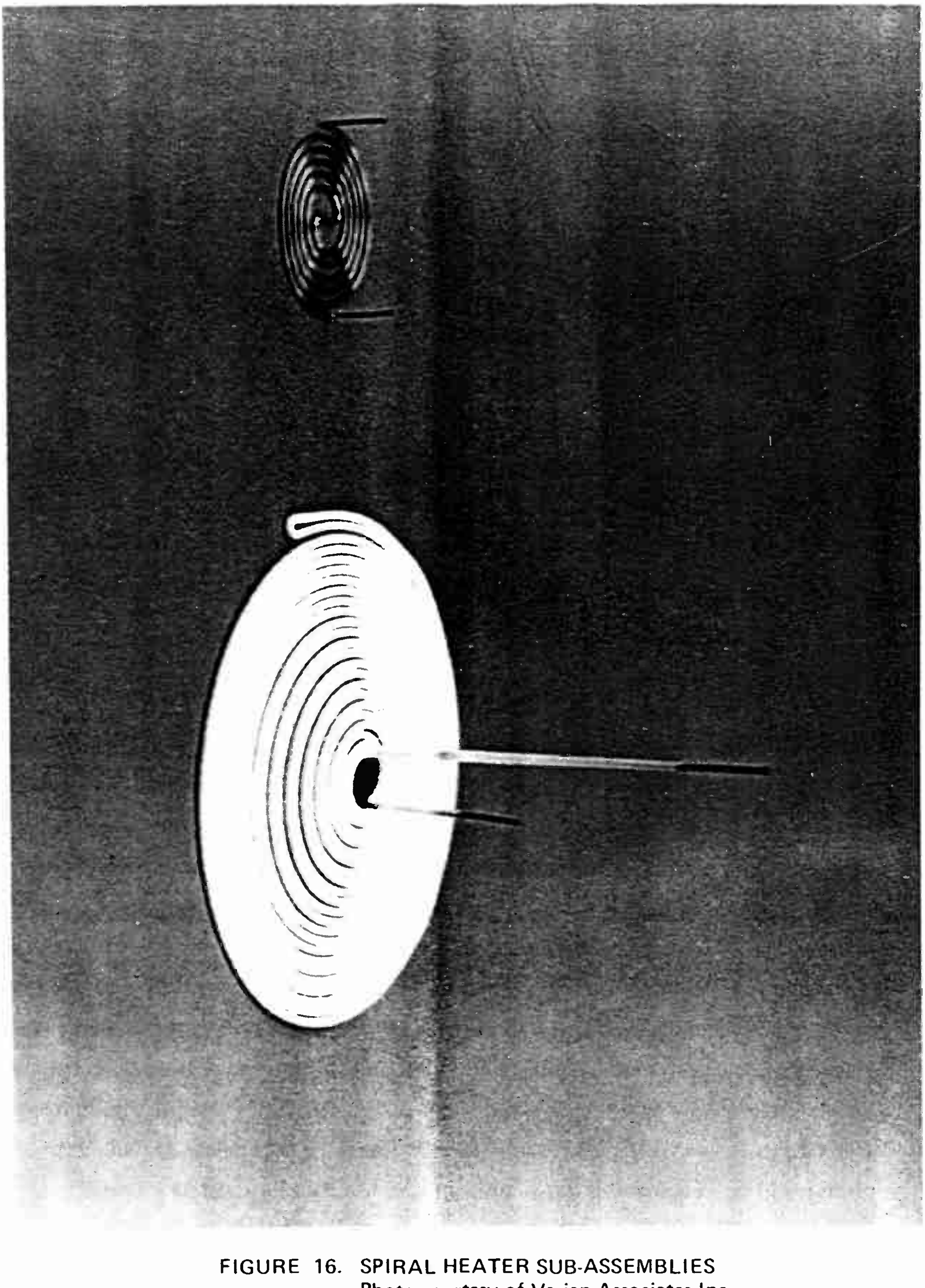


FIGURE 16. SPIRAL HEATER SUB-ASSEMBLIES
Photo courtesy of Varian Associates Inc.

The heater package illustrated in Figure 15C is an encapsulated or potted heater, a design that is being used more and more on various types of klystrons and other microwave tubes. This type of heater is normally cylindrical in shape as shown, with the heater wire being held in position by sintered alumina powder. The heater is first positioned in the cylinder and the alumina powder is packed around the heater, coming in contact with the surface of the wire and the back side of the emitting substance. The heater package is then heated to a very high temperature in a furnace (2800° C/5072° F to 3000° C/5432° F) to harden the alumina powder, in the same manner as with the alumina coating on the heater wire.

Encapsulated heater packages are designed to be used with cathode emitting materials that require operating temperatures of approximately 1000° C (1832° F) to 1200° C (2192° F). The heat transfer capability of this design is much better than the others described, since the alumina is in direct contact with the cathode and is a good heat conductor. This enables temperature differences of only 200° C (392° F) to 300° C (572° F) between the heater and cathode, but the warm-up time is longer than the un-potted heaters because of the added mass and weight of the alumina.

3.2 Cathodes (Emitters)

The cathode is the heart of a vacuum tube, and tube operation will be adversely affected by poor cathode performance. Cathodes are materials which emit electrons under the influence of an activating energy and generally in the presence of a confining electric field which induces the electrons thus released from the cathode surface to travel in a desired direction.

Depending on the form of activating energy - heat, light, or other means and the physical shape of a cathode, many different classifications of cathodes are possible. Pure metal emitters, film cathodes, composite cathodes, oxide cathodes, dispenser cathodes and matrix cathodes are all different types of cathodes. These classifications can also be divided into subgroups, and even a description of the various types of cathodes in terms of composition and structure or combinations of materials, requires a book length treatise to explain. Many textbooks are available for those readers who desire to go further than will be covered here. We shall discuss those cathodes which are of most interest to UHF-TV klystron users and only to a degree of detail that is practicable. Inasmuch as our item of concern is emission from metal, which may or may not be pure metal or one with a coating of certain chemical elements, we shall now briefly review the actions of atoms and molecules in metal.

All matter consists of two basic electrical charges, positively-charged protone and negatively-charged electrons. These charged particles are the fundamental building blocks which form the atoms comprising the elements of all matter.

Atoms and molecules confined in a given volume of any metal are in a state of random motion around a mean position. The extent of the motion is determined by the nature of the substance and its temperature. In solids, this random motion is most restrained. In liquids the restraint is less. This explains why a solid substance holds its shape unless forces are applied to change it and why a liquid changes its shape to suit its container.

If the temperature of a metal is reduced, its amount of random motion is reduced, and its resistance to the flow of electric current is also reduced. For example, a liquid turns to a solid if the temperature is reduced far enough, and on the other hand, if the material is heated, this energy added to the energy already possessed by the atoms and molecules in motion will cause them to perform greater movements at greater velocities.

Free electrons in a substance held at room temperature perform only random motion in their travel between atoms, as illustrated in Figure 17. Surprisingly, these electrons move at a relatively high velocity. We might then wonder why don't they move out of the material or why they don't break through the surface and get into free space. Some electrons do just that, but they are few in number and we shall disregard them for now.

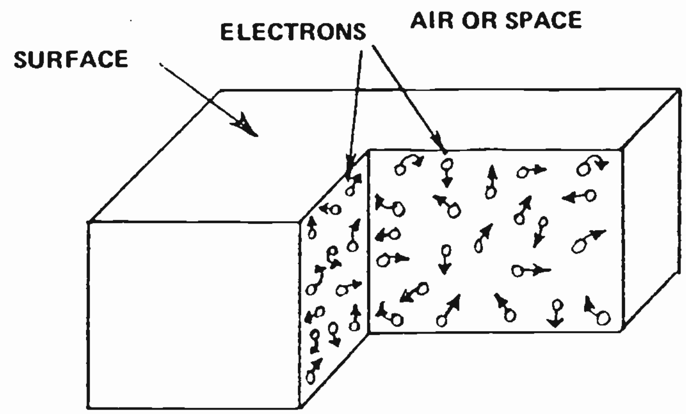


FIGURE 17: RANDOM MOTION OF FREE ELECTRONS IN METAL AT NORMAL TEMPERATURE

The generally accepted description of electron motion, then, is that there is no liberation of electrons because the boundary of the substance exerts a force toward the inside of the substance, and so presents the electrons from leaving the material, unless special conditions are created deliberately. For an electron to break through the surface, it is necessary that its velocity, as it approaches the surface, be greater than a critical amount, in order that its kinetic energy be sufficient to overcome the barrier which tends to contain it. (See Figure 18.)

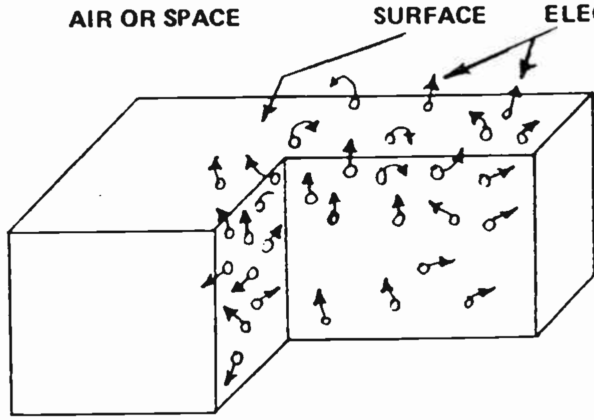


FIGURE 18 FREE ELECTRONS ESCAPING INTO SPACE AND TO SURFACE OF METAL

This atomic behavior of different metals is described as its work function, which is a constant. As a matter of convenience, this constant is usually expressed in electron volts. The work function is different for various metals; e.g., tungsten is 4.52, thoriated-tungsten is approximately 2.0, nickel with an oxide coating (barium oxide/ strontium oxide) is approximately 1.5. The lower the rating, the more easily an electron can penetrate the surface and leave the material. It should be noted that work-function constants may vary from one reference book to another; this is usually due to the particular conditions under which the measurements were originally made.

We have now shown, that by applying sufficient energy in the form of heat to the emitting substance, we will have electron emission. Typically, most cathodes operate at some temperature between 800 to 1200° C (1472 to 2192° F). For each type of cathode there is also a definite rate of thermionic emission at each temperature. There are many areas of importance in selecting an emitter. The three basic ones are as follows:

1. The current density measured in amperes per square centimeter of emitting surface (A/cm^2)
2. Operational voltage applied between cathode and anode
3. Operational mode such as cw or pulse

3.2.1 Oxide Cathodes

The most commonly used emitter in the last 50 years is the oxide-coated cathode. It is still the most efficient one because of its high electron emission at relatively low temperature. Its coatings are usually barium and strontium oxides from which the emission takes place when operated at temperatures typically from 800° C (1472° F) to 1000° C (1832° F). Two forms of the oxide cathode are shown in Figure 19, both with a base metal of nickel.

A mixture of alkaline-earth carbonates and some suitable organic binders are applied to the nickel base until the required thickness is reached. The coating is then thermally decomposed in vacuum to obtain the thermionically active oxide surface. This is accomplished by passing current through the heater in order to heat the cathode surface. Figure 19A illustrates a smooth nickel-base oxide cathode. This type may be used on tubes that operate to approximately 5000 V. In Figure 19B, the oxide coating is mixed with nickel particles that have been attached to the nickel base. This type of cathode has the advantage that it can be operated at much higher voltages and is not as susceptible to having the oxide coating peeled off by electrostatic fields. Any of the heater packages shown in Figure 13 may be adapted to these packages. As a matter of academic interest, some reference material states that oxide-cathodes are thought to be an N-type semi-conducting solid[2], with donors responsible for the emission, the nature of which has not yet been fully established. To put it simply, donors are elements or atoms with an excess of negative electrons. Whatever the donors are, the majority are created when the cathode is first heated, and this so-called thermal activation is the creation of donors by partial reduction of the oxide at the metal-oxide interface.

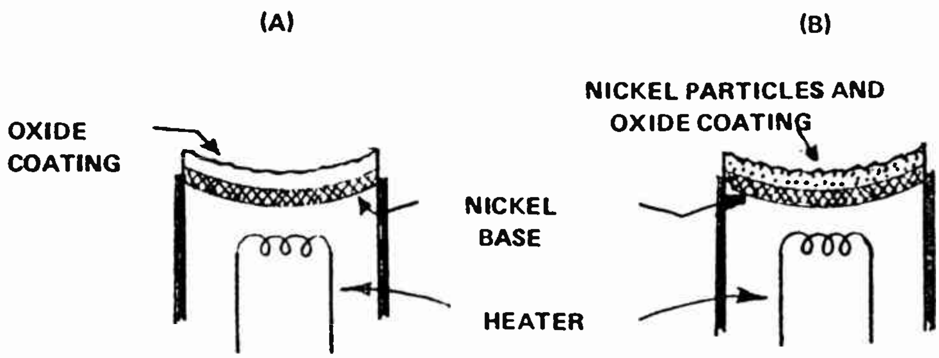


FIGURE 19 : TYPES OF OXIDE CATHODES

There are many factors that are thought to contribute to the decrease in emission with life to oxide cathodes. Among the most common of these are processes whereby the overall donor concentration decreases. These processes can be either in the form of a decrease in donor production rate, such as a depletion of reducing agents in the base metal or the thermal evaporation of donors, or they can be an increase in the donor loss rate as would be experienced from the buildup or residual gases in the tube.

Other factors that determine the end of useful life which may be more familiar to the reader are effects that cause the mechanical destruction of the coating, such as sparking, flaking, ion-bombardment or excessive heating of the cathode which causes over-rapid evaporation of the coating. In general, it can be said that oxide cathodes give good emission at relatively low temperatures but suffer from mechanical shocks. They demand cleanliness in construction and are not suitable for operation in a poor

---

[2] Thermionic Electron Sources by G.A. Hass, NRL Report 5657, October 6, 1961, and Electron Tubes by Walter H. Kohl, Reinhold Publishing Company, New York, 1960.

vacuum, since they become permanently poisoned by fairly low pressures of various gases that are found in vacuum tubes.

3.2.2 Impregnated Cathodes

The most common emitter for high-powered klystrons is the impregnated cathode. It is interesting to note that the terms "impregnated", "matrix" and "dispenser" have all been used as general terms to describe the same type of cathode. "Matrix", very simply is a substance in which minerals are embedded; the "dispenser", dispenses active materials in its surface, and the "impregnated" cathode means basically the same as matrix. Since the term "impregnated" more closely describes three types, we shall use this term to describe the cathodes dealt with in this portion of the text.

While the construction and exact nature of the impregnated cathode may vary between the different types, they all have similar emission characteristics and their lives are measured in terms of thousands of hours at emission levels described in terms of amperes per square centimeter. The impregnated cathode has been in use for about 50 years in some form or another. Certain structural weaknesses and chemical instabilities in oxide-coated cathodes has led development towards emitter constructions capable of withstanding more mechanical, electrical and chemical stress forces which are prevalent in many modern, cathode applications.

One type of impregnated cathode uses porous tungsten, throughout which is dispersed the active material, often a barium compound. (See Figure 20.) The range of porosity of the tungsten before it is impregnated may be from 15 to 25%, depending on the degree of emission activity required. A number of variations of this cathode have been made by the use of various active emitting agents and methods of processing. Operating temperatures are typically 900° C to 1200° C (1652° F to 2192° F), and it is possible to achieve CW current densities of 1 to 3 A/cm^2. Figure 20 illustrates a typical cathode/heater package using a potted heater, although the other heater packages covered earlier in Figure 15 may also be used with these cathodes, the choice being predicated on the requirements of the completed gun assembly and physical size.

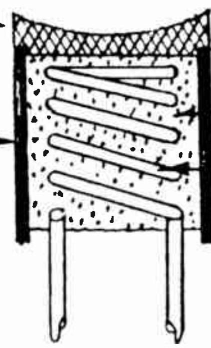


FIGURE 20 : IMPREGNATED CATHODE

On larger cathodes, it is often an advantage to use the encapsulated heater package as shown above, or a variation of the flat heater attached to the back of the cathode button as previously described. This allows the heater to operate at lower temperatures and still transfer the added energy required by the larger surface area. The life of a cathode naturally depends on the operating temperature. In laboratory studies, for example, test results on some cathode designs which operated at approximately 1100° C (2012° F), were estimated to have a life expectancy of 15, 000 hrs. With a reduction in temperature to approximately 1000° C (1832° F), the life expectancy was estimated to be extended to about 32, 000 hrs. This would also work in reverse if more emission is needed. Generally speaking, an increase in operating temperature of 50° C (122° F) will increase the emission density by a factor of 2, but the life expectancy will also decrease.

While these figures may be impressive, they were obtained under laboratory conditions and we should not expect that by merely lowering the operating temperature of the cathode, that we may expect an increase in operating life. Conversely, it may do more damage than good, and we shall explain this point shortly. For now, the reader should note that cathodes are designed to operate within certain temperature ranges and a decrease below or above that point may cause adverse effects.

It is often the practice for klystron users to either lower or raise the operating temperature of the cathode (lowering or raising the heater voltage) for one reason or another and this adjustment gives what appears to be excellent results with an increase in operating life. However, this should not be a common practice for the klystron user. It is always advisable to consult with the tube manufacturer before attempting this procedure, as not all tubes respond favorably to this adjustment. It should be of interest to the reader the measures that are taken to produce and preserve an adequate vacuum and emission after the vacuum pumps have done their job. The processing of all parts is done with extreme care so that their surfaces are essentially free of contaminants and absorbed gases. All of these surfaces will be eager to take up gases and there is no need for getters, the clean components act as getters.

Barium, which is present in most cathodes to some degree, also absorbs many of the small quantities of residual gases without damage, i.e., it has a relatively high sorptive capacity for the gases encountered in vacuum tubes. However, surfaces which have a porous texture, in particular oxide cathodes, have a great tendency to absorb large quantities of gases when they are colder than other parts of the tube from which gases are released, and this may lead to poisoning effects. One should never operate a cathode below its recommended temperature.

The impregnated tungsten cathode in Figure 20 is also susceptible to low-temperature poisoning, but not to as great a degree as the oxide cathode. Generally, the impregnated cathode has the ability to recover from severe poisoning effects better than the oxide cathode because of its ability to repeatedly provide a new surface by diffusing barium from within the porous metal base. However, repeated poisonings cause the time for reactivation to become longer each time it occurs. Several studies have been made on the poisoning effects of various gases on these cathodes, and it has been found, for example, that for an operating temperature of about 1100° C (2012° F), there is a critical pressure (e.g., $<10^{-7}$ or $<10^{-6}$ mmHg) of these gases that must not be exceeded if we are to avoid poisoning. Other gases that may cause loss of emission of the cathode are some metal vapors. The most common reason is, of course, the typical vacuum leak to air.

Loss of emission or poisoning is often caused by heavy overloads or voltage transients associated with the cathode. The electron gun, while operating, will also act as an electrostatic collector of dust and moisture from the surrounding air. Thus, the cathode becomes very susceptible to external arcs across the vacuum seals of the electron gun, and it may create a small vacuum leak by puncturing a seal with the high-intensity arc. Tubes that are water cooled and have developed small water leaks also cause arcing when water drops across the high-voltage seals of the electron gun. Electron guns that have exposed ceramic seals are more susceptible to this problem than ones with an insulating covering such as silastic[3].

The main purpose of silastic or RTV is for electron guns that have short ceramic seals between the high-voltage points and ground, to reduce or eliminate arcing across short distances at relatively high voltages, but silastic covering is not a cure-all for arcing due to moisture across high voltage seals. Many klystrons that have electron guns with large ceramic seals do not need silastic covering. Prevention of water leakage in a system is the best way to solve an arcing problem.

Voltage transients can also trigger internal arcing across small microscopic particles or nodules on the internal surfaces of the cathode structure or anode. This internal arcing vaporizes these small particles of metal or other substances, causing the internal pressure of the tube to increase, usually with a loss of emission. This phenomenon is generally referred to as "gassing". Internal arcing also causes pitting of the metal structure, thus increasing the possibility of repeated arcing. The reader can understand how this action has a compound effect. Each time there is an arc, the surface of the metal gets progressively more pitted, thus causing more arcs. However,

---

[3] Silastic: A registered trade name for silicone rubber RTV.

all internal arcing is not created by small particles. Some internal arcs are caused by an external arc, which created a small pin hole. This pin hole allows the tube to leak a small amount of air, which in turn, triggers internal arcing very easily. (If the klystron user performs his first echelon maintenance by keeping the electron gun clean, external or internal arcing should be minimal, but no one can guarantee that a large tube such as a klystron will never arc.)

Normal end of life, disregarding catastrophic failures, occurs when the active coating agents (e.g., BaO-W) have been depleted and a chemical reaction takes place accompanied by the release of oxygen-bearing poisoning agent.

3.2.3 Advantages of the Impregnated Cathode

Generally, the impregnated cathode has the following advantages:

A. A larger volume of active material can be added to the base material.

B. The active material cannot be peeled off by high electrostatic fields at high anode voltages.

C. It can operate at high current densities and at high pulse-duty cycles.

3.2.4 The Pressed Nickel-Oxide Cathode

Another version of the impregnated cathode is the pressed nickel oxide cathode. It is not a widely used cathode on UHF TV klystrons. However, it has been used on many microwave tubes with excellent results.

The method of fabrication may vary from one manufacturer to another, but in general, this type of cathode is composed of a misture of nickel powder (Ni) and alkaline-earth carbonate powder. This completed mixture can be pressed into suitably shaped dies, sintered, and machined to any given configuration (similar to Figure 19B).

The emission characteristics and work function are similar to oxide-coated cathodes. It is not considered a true diffusion-type cathode which derives most of its emission from a continually replenished barium oxide on a metal substrate, as is the case with impregnated tungsten cathodes. Instead, it is essentially a patchy oxide cathode with the structural advantages of a metallic support. It does have the advantage of being able to withstand mechanical shock and vibration, as well as electrical sparking and ion-bombardment much better than oxide cathodes.

Conversely, it does suffer the same losses of emission that are caused by donor migration, gas poisoning and flaking of the coating, as with oxide cathodes. It can be machined into intricate shapes and close tolerance, but it is difficult to fabricate and harder to activate than the oxide cathode.

3.2.5 Electron Emission

In the preceding section, we discussed thermionic emission and the necessity to raise the temperature of the emitting surface to the point where the electrons can break through the surface barrier of the metal. The heater built into the cathode structure (which is operated as a low voltage, such as 6.3V) provides the heating power necessary to raise the temperature of the specially-prepared metallic surface of the cathode to the point where it will emit electrons.

The emission from the cathode forms a dense cloud of electrons (refer to space charge paragraph 3.4) in the vicinity of the emitting surface (see Figure 21). Under these conditions, there is emission but no electron flow.

Electronic emission is of little use in the operation of a vacuum tube if it cannot be controlled and utilized for practical purposes. Since the emitted electrons carry a negative charge, they will tend to move toward an object that has a positive charge.

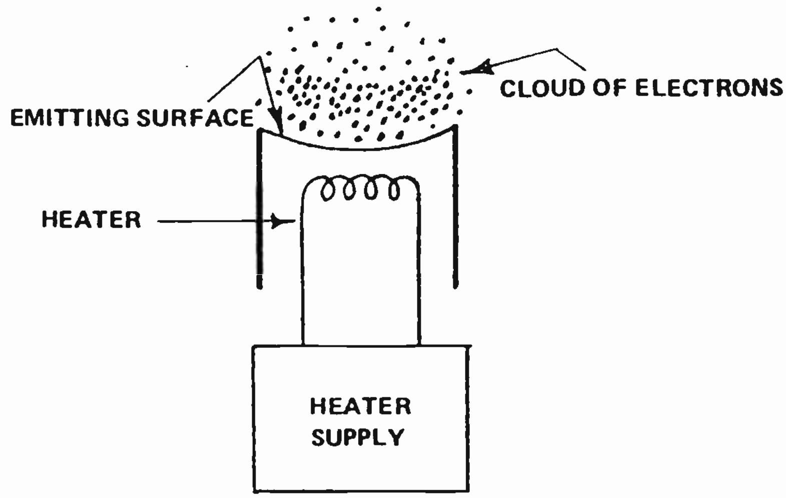


FIGURE 21 : ELECTRON CLOUD

In opposite fashion, they will tend to be repelled by any element that is negatively charged, and will simply stay in equilibrium as an electron cloud if there is no positive or negative force present.

In order to have a complete electronic circuit, there must be an additional element to receive these electrons. This element is positively charged and is called an anode, and without this additional element to complete the circuit, the cloud of electrons will remain around the cathode surface.

3.3 Focus Electrode (Beam-Forming Element)

An essential part of the overall operation of a high powered klystron is a dense, smooth, well-formed electron beam. The initial step in focusing the electrons emitted from the cathode of an electron gun is accomplished not by one element but by the relative position, shapes, and potentials applied to all elements. The complete electron gun is similar to the lens in a projector, the object being to get as much electron current flowing into as small a region as possible without distortion or fuzzy edges.

The focus electrode or beam forming electrode is an important part of the total electrostatic lens that is created. The focus electrode is typically a specially formed cylinder that is placed slightly ahead of the cathode emitting surface, and is normally connected electrically to the cathode and operates at the same potential. The purpose of the focus electrode is to help form an electrostatic lens between the emitting surface and the anode, so the electrons leaving the cathode surface will be focused to a point some distance beyond (see Figure 22).

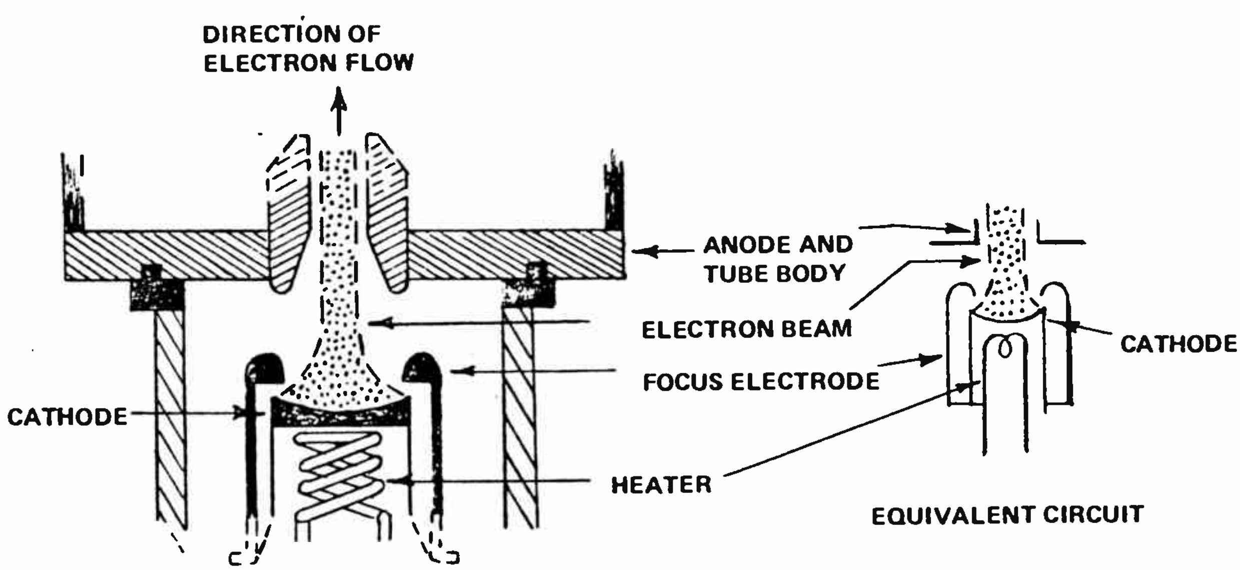


FIGURE 22: ELECTRON BEAM FORMATION

How is this electrostatic lens formed? Consider first, two parallel conductors with a potential applied between them (see Figure 23). An electric field will be established in the space surrounding the conductors. All points in this space at different distances from the conductors will have different potentials with respect to the conductors - depending on the positions of the point. This difference of potential between the two conductors results in a stress in the dielectric and a storage of electrical energy. There will also be a force of attraction between these two conductors.

The distribution of the electric field is shown by the dashed curved lines between the conductors. The lines leave a conductor at right angles to the surface and have a direction the same as that in which a positive charge of electricity would move. The lines of electric flux differ from the magnetic induction, which are continuous and exist inside the material as well as in the area surrounding the material.

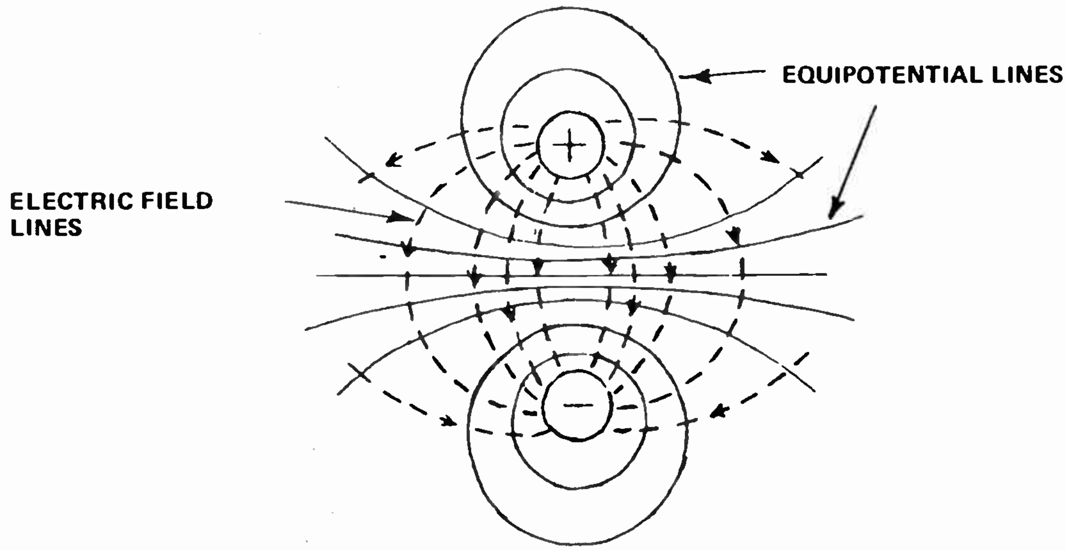


FIGURE 23: LINES OF FORCE AND EQUIPOTENTIAL LINES NEAR TWO EQUAL CHARGES OF UNLIKE SIGNS

If lines are drawn through all points having the same potential with respect to one of the conductors, then we have circles surrounding each conductor but somewhat eccentric (solid lines in Figure 23). These circles are known as equipotential lines, and it should be noted that the equipotential lines have the same form as the magnetic flux which would surround these conductors if they were carrying current.

Thus, if the equipotential lines can be drawn, the lines of force can be immediately constructed, they being at all points perpendicular to the equipotential lines which they intersect.

Consider now, two concentric cylinders with a potential applied between them (Figure 24A), showing the equipotential lines only. This same action also takes place between the beam forming electrode and the anode of the klystron (Figure 24B), the degree of electrostatic lens focusing being determined by the size, shape,and position of the focus electrode and anode.

Once the electrons are focused so they form a small diameter beam beyond the anode,they must be maintained at this size through the length of the klystron.

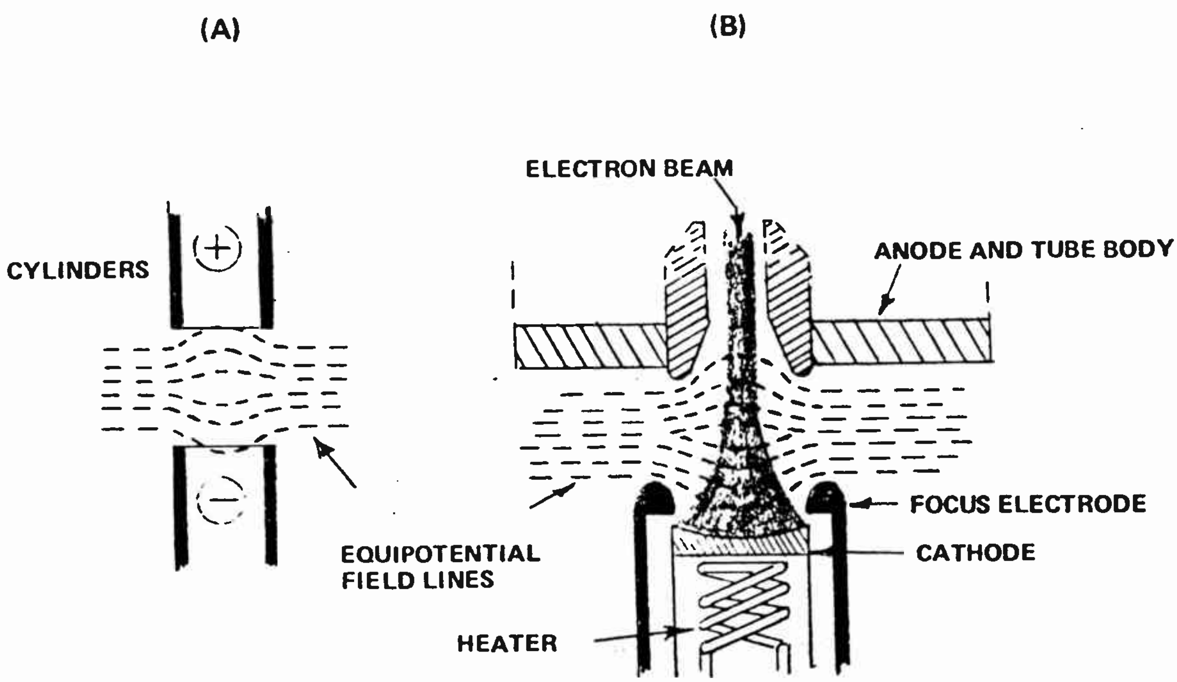


FIGURE 24: BEAM FORMATION IN ELECTRON GUN

If the stream of electrons is not contained, as they pass through the anode aperture , they will diverge rapidly because of the mutual repulsion of the electrons, thus melting the anode and drift tube. To confine these electrons beyond the anode and through the rf structure, additional focusing means are required. An axial magnetic field, parallel to the electron beam will provide this additional focusing (see Figures 12 and 27).

3.4 Space Charge

At this point it is important to understand a certain action inside the tube. Regardless of what may be connected between the cathode and anode, or if no connection of any kind is joined to these electrodes, an electron cloud will always appear near the cathode as soon as the cathode is heated to electron emitting temperature (see Figure 21 again). What happens to these electron charges?

The electron gun section (cathode-anode) of the klystron, or any similar microwave tube electron gun, can be considered as a diode since the emission characteristics are the same (see Perveance section). With this understanding there are a number of basic conclusions that can be stated regarding diodes.

(1) Current flow in a diode occurs only when the anode is positive with respect to the electron emitter.

(2) Current will not flow in a diode when the anode is negative with respect to the electron emitter.

(3) Current flow in a diode can be in one direction only, from cathode to anode, never from anode to cathode.

(4) A diode can behave like a control valve, automatically starting and stopping current flow.

The above statements should then lead one to ask: How much electron emission is possible? How much anode current is possible or permissible? How high can the voltage be on the anode? These questions require answers because they influence the understanding of the overall operation of the device, and this, in turn, leads us to the subject of space-charge.

There are four important factors that determine the number of electrons which traverse the space between the cathode and anode in a diode per unit of time. (One may consider this as beam current if it is easier to relate to.)

(1) The operating temperature of the cathode.

(2) The emission per unit of time.

(3) The voltage of the anode relative to the cathode.

(4) The space-charge.

It should be obvious that items (1) and (2) are directly related because the operating temperature of any cathode determines the number of electrons emitted per unit of time. In item (3), the anode voltage is the determining force attracting the emitted electrons. At first thought, it would appear that a low value of anode voltage would attract all of the electrons which have been liberated from the cathode. This does not happen because of item (4), the space charge. The control of the beam current in diodes is generally described as being space-charge limited.

The term space-charge refers to the effect on the electrons which have been liberated and accumulate in the vicinity of the cathode, with or without electron current flow in the tube. By examining this behaviour of the space charge, it will show why changes in the value of the voltage applied between the cathode and anode change the value of beam current.

Consider no a tube (diode) as illustrated in Figure 25A, with the cathode heated to an electron-emitting temperature and with the anode joined to the cathode. Since no voltage is applied to the anode, it exerts no attracting force on the emitted electrons. What happens to them? First, it is necessary to make a few assumptions. The heat applied to the cathode supplies sufficient velocity to the electrons to enable them to overcome the work function of the emitting material (refer to Section 3.2). After the electrons penetrate the potential barrier they are at a relatively low velocity because most of the energy contained by the electrons is given up passing through the barrier. It is true, though, that a few emitted electrons can possess sufficient velocity to complete the excursion to the anode without any attracting pull from the anode. However, they are so few in number that they can be disregarded in terms of basic operation of the tube.

For ease of explanation, let us next assume that the shape of the emitting surface of the cathode and anode are both a straight side or flat plane. The final assumption is that you are able to view, from a point in space between the cathode and anode, the electrons leaving the cathode in an orderly manner and motion, similar to the movement of troops passing a reviewing stand in columns (see Figure 25B). This is not exactly true, because emission is essentially haphazard and in random directions away from the cathode surface. However, this orderly emission concept is useful in this analogy and will help in better understanding what will follow.

The first row of electrons that were emitted have traveled forward with nothing in front of them to slow their progress. However, as mentioned earlier, their low velocity is a limiting factor, and each row is affecting the next row behind it, and so on.

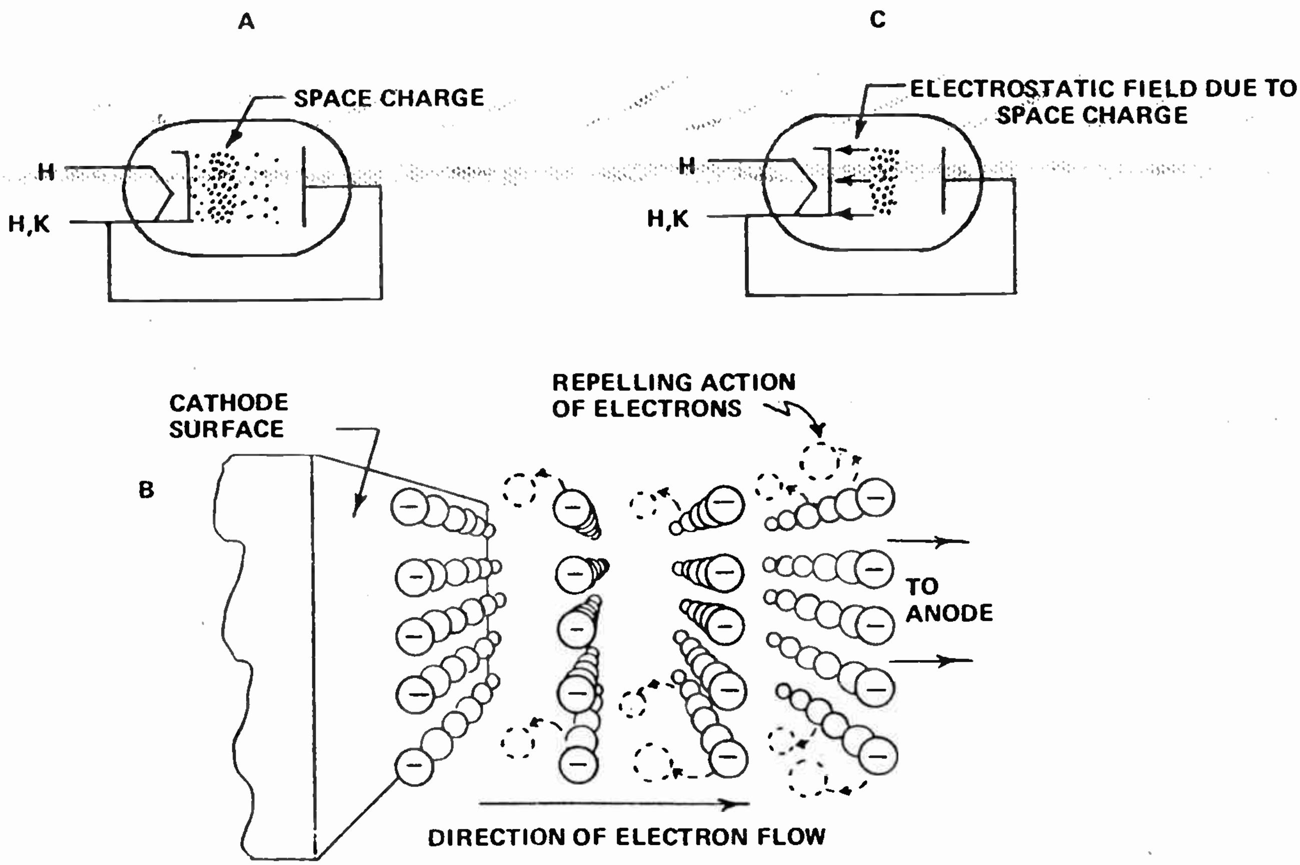


FIGURE 25: ACCUMULATION OF ELECTRONS IN DIODE

Since the basic law of charged bodies states that like charges repel each other, so each row of electrons in back of the first group are experiencing a repelling force, and the direction of this force is such as to retard the motion of the remainder of the electrons in their advance away from the cathode.

Because a retarding force acts on both sides of the groups of emitted electrons and subsequently emitted electrons, the result is a cloud of electrons near the cathode. The denser accumulation of electrons is nearest the cathode and less and less dense ones are progressively, further away from the cathode similar to Figure 25A.

It would appear at this time that with each group of electrons being emitted from the cathode, there would eventually be nothing but a bunch of useless electrons bumping into each other. Actually this does not happen. Since each charge in space exerts an influence upon each adjacent charge, the accumulation of the charges in space presents a cumulative effect of great importance. This condition is an electrostatic field called a space-charge that exists between the boundary of the electron cloud and the emitting surface of the cathode similar to Figure 25C.

How does this electrostatic field counteract the accumulation of electrons in the electron cloud ? First, the lines of force of this field in reference to the emitted electrons is away from the electron cloud. Next, the cathode surface is in essence the positive boundary of the electrostatic field, because as each negative electron leaves the cathode surface during emission (the cathode contains one additional positive ion; an atom lacking one or more electrons) and tends to attract electrons back in itself.

As we mentioned earlier, the density of the space charge does not increase just because the cathode is continuously emitting electrons, and for any given temperature of a cathode, the emission is definitely limited as is the density of the space charge. When the space charge acquires a critical density at a given emission level, the space charge develops a field of such intensity as to repel back into the cathode, one electron for every electron which enters the electron cloud. This equilbrium condition in the space charge is called emission saturation.

What happens if you raise the operating temperature of the cathode, establishing a new level of emission saturation? As stated above, the space charge will again reach a condition of equilibrium. When the cathode temperature is increased, the velocity of the electrons being emitted will increase. The new electrons, added by the increase in temperature, enter the space charge and make it more dense. When the density has reached a new level where the field strength can offset the increased velocity of the electrons, a new level of emission saturation is again reached. It should be obvious now that the space charge has a controlling influence upon the emission of electrons from the cathode.

If a voltage is now applied between the cathode and anode, how does the space charge influence the beam current? This is graphically shown in Figure 26. The voltage applied to the anode is positive relative to the cathode, and in between these two electrodes is the space charge with its retarding influence on the emitted electrons. With the positive voltage applied to the anode, there are now two electrostatic fields, one between the cathode and space charge and the other between the space charge and the anode. Because this space charge is between both electrodes, the attracting force of the positive anode acts upon the electrons in the space charge, rather than directly on the electrons being emitted.

This is a simplified approach, but can be shown to be true for the following reasons. In Figure 26, the electrostatic lines of force between the space charge and anode are going to the positive anode and represent a certain number of excess positive charges on that anode, and naturally a deficiency of negative charges.

Since the electron cloud (space-charge is located between two electrodes, it supplies the number of negative charges required for the field created by the positive voltage applied to the anode. The movement of an electron between the cathode and anode can, therefore, be viewed as being first into the space-charge region and then

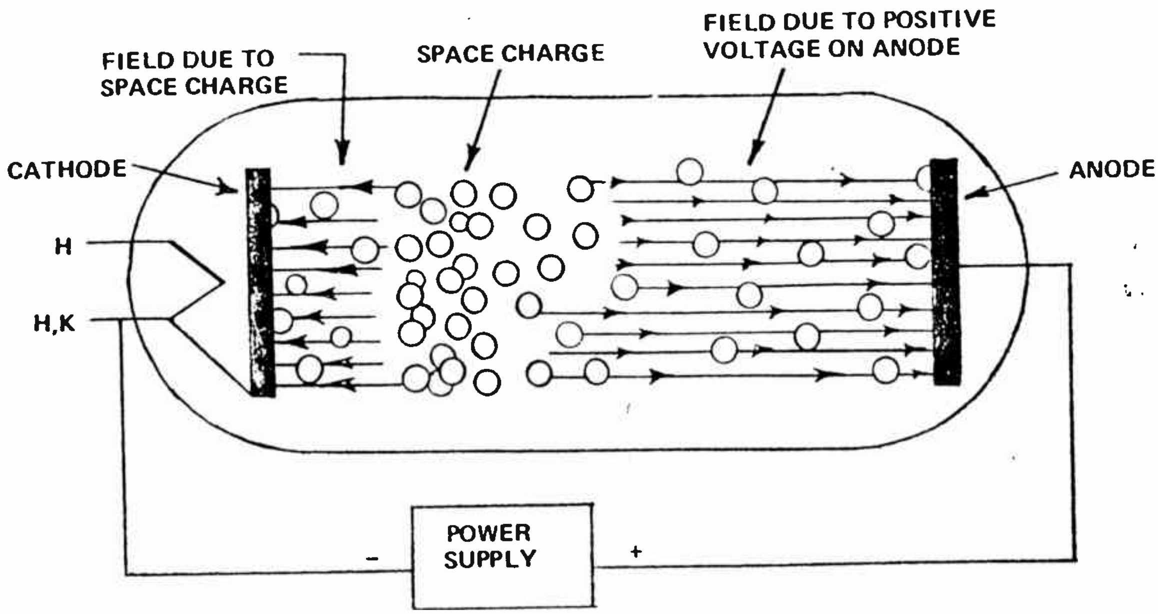


FIGURE 26: ELECTROSTATIC FIELDS PRESENT BETWEEN CATHODE AND ANODE DUE TO SPACE CHARGE

out of the space-charge region to the anode. In this manner, a constant electron density is maintained in the space charge. If the beam voltage is increased, increasing the number of electrons attracted by the anode from the region that is near the anode, the density or equilibrium of the space charge will be disturbed. It will cause a reduction of the magnitude of the field of the space charge. The ability of the space charge to repel electrons emitted from the cathode is therefore reduced and, consequently only that number of electrons required to restore equilibrium will be added to the space charge in the region near the cathode.

It should now be obvious that the space charge is a necessary function in a vacuum tube. In most vacuum tubes, the cathodes are designed to be capable of supplying a surplus of electrons so that more of them are available than are actually required. If there were no space charge, even a low beam voltage would result in high values of beam current and shorter cathode life. Some control is needed, and this is accomplished by the space charge.

3.5 Electron Flow

Up to this point, the discussion has been restricted to explaining the functions and construction of the various parts of an electron gun. Consideration will now be given to the operation of the complete electron gun assembly regarding electron flow through the complete tube.

In order to employ such an electron gun in a useful device, some provision must be added for controlling the electrons. Since the electron is a particle of negative electricity, it is attracted by a charge of opposite polarity. We have shown that by adding a second electrode (positively charged) in front of the cathode, called an anode, we will then have electron flow. The anode, as mentioned earlier in the text is not an integral part of a basic electron gun, it is actually part of the tube body input polepiece, but is a necessary part of the electron beam circuit.

It has also been established that, by adding an anode in front of the cathode, the electron gun section takes on the characteristics of a diode, and that if a voltage is applied between the emitting cathode and the anode, there is a definite electron current drawn. The amount of current drawn is determined by the following relation (see also section on Perveance):

$$I = K (E)^{3/2}$$

Where:

I = Beam Current

E = Beam Voltage

K = Perveance, a constant for any particular klystron, which is dependent upon the cathode-to-anode spacing inside the tube.

At suitable voltages, the electrons emitted from the cathode first form an electron cloud (space-charge) and are then drawn toward the anode which is positively charged. They are focused by the electrostatic lens created by the focus electrode and anode. The initial velocity of the electrons is determined by the difference in potential established between the cathode and anode.

Another important factor that determines the velocity of the electrons (or force of attraction) is the distance between the cathode and anode. The smaller the separation, the greater the force for a given value of applied voltage. If the voltage is doubled, the force of the field is doubled, and this has the same effect as reducing the distance between the cathode and anode by half.

As the confined beam of electrons enters the anode region of the klystron, another force acts upon the electrons. Due to the mutual repulsion space-charge force within the electron beam, it will cause the beam to expand rapidly if not confined. In other words, each negative electron wants to repel the next adjacent electron. Consequently, they tend to spread out. So a magnetic field, parallel to the direction of the motion of the electrons, is introduced at this area, covering the length of the klystron body (see Figure 27). The confined electrons will thus continue their travel toward the collector which is also positively charged. At the end of the klystron, the electron beam strikes the collector electrode, which dissipates the beam and returns the electron current to the beam power supply.

It is important to know that the stream of electrons traveling from the cathode to the collector does not need to travel through rf cavities in order to reach the collector. For all practical purposes, the electron beam (without rf applied to the tube) needs only a straight pipe to allow it to travel from the anode to the collector. In Figure 27 this is symbolized by showing the cavities in broken lines.

The magnetic field is normally terminated as quickly as possible after the last cavity so that the beam can spread evenly before it hits the collector. This tends to spread the electron beam interception over a larger surface of the collector and minimizes the kind of collector cooling problems which would result if the beam was still concentrated at the time of interception (see section on Magnets). Even with an axial

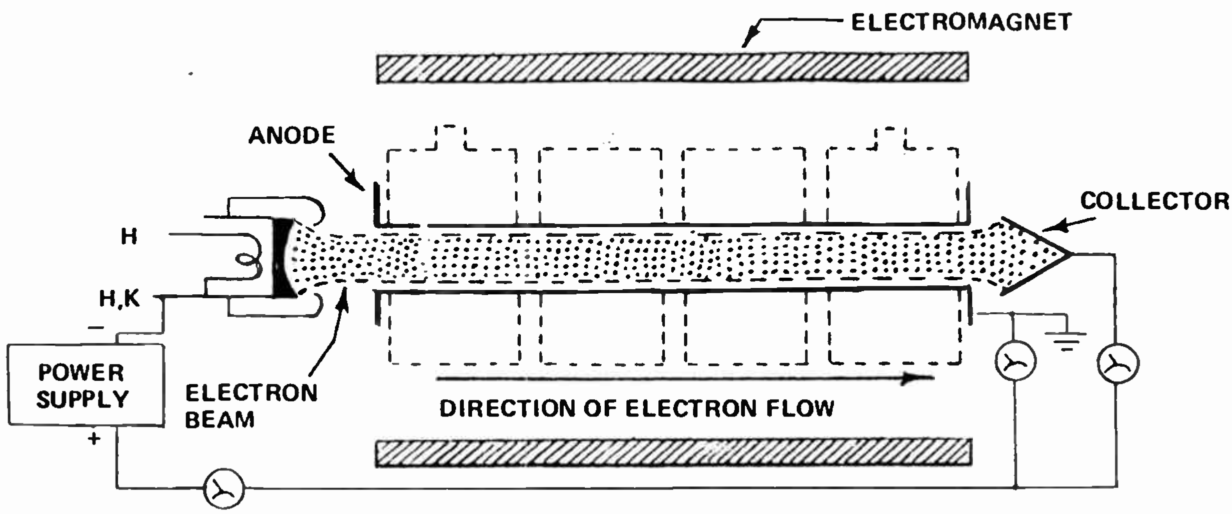


FIGURE 27: ELECTRON FLOW WITHOUT RF CAVITIES

magnetic field, some electrons go astray and do not remain in the main electron beam. These electrons will be intercepted by the anode or the drift tubes as they travel from the cathode to the collector and are measured as body current.

The collector on a klystron acts much like the plate of a triode insofar as collecting of the electrons is concerned. However, there is one important difference. The plate of a triode is normally connected in some fashion to the output rf circuit; whereas, in a klystron amplifier, the collector has no connection to the rf circuitry at all. You will also note that the collector and body appeared to be tied together and then grounded (Figure 27), yet show separate metering circuits. An oversimplified answer to this is that the resistance in the metering system is enough to electrically separate the collector and body for monitoring.

It is also true that some klystrons are built with the collector directly attached to the body of the tube with no insulating ceramic window separating the collector and body. Such a tube functions in the same manner as any klystron, the only difference being that you cannot monitor body current separately.

Klystrons that are built with a grounded collector are generally tubes that operate as high energy levels and have a problem with rf radiation out of the collector ceramic insulator. The collector and body currents are measured as a total value in this case.

Do not attempt to shield or ground the collector to the body of a klystron that is built with an insulated collector. The separate metering circuits for the body and collector will not function properly, the body current meter will attempt to indicate the same as the collector and will be damaged. Special rf shielding methods are used for insulated collectors and should not be changed.

3.6 Modulating-Anode

Until now most of the text has been confined to discussions using a cathode control electron gun in order to establish basic operating fundamentals of electron guns. In summarizing the last few sections (Sections 3.3 through 3.5), we have now established the following important operations of electron guns:

1. Beam forming by creation of an electrostatic lens between the cathode and anode.
2. Comparison of electron guns to diode operation.
3. Control of electrons by space charge.
4. Electron flow in the complete tube.

Consider now the addition of another element to the electron gun, a modulating anode, placed between the cathode and accelerating-anode. What happens to the above four relations of electron gun operation when we add a modulating anode?

If one were starting to design an electron gun, there would, of course, be some fundamental design restrictions, but for purposes of this discussion, there are no differences except the electrostatic lens. The electrostatic lens is created in the same manner except that it occurs mainly between the focus electrode and the modulating anode (see Figure 28).

This region of the electron gun also has the characteristics of a diode, the space-charge action is still the same and the flow of electrons through a completed tube is the same.

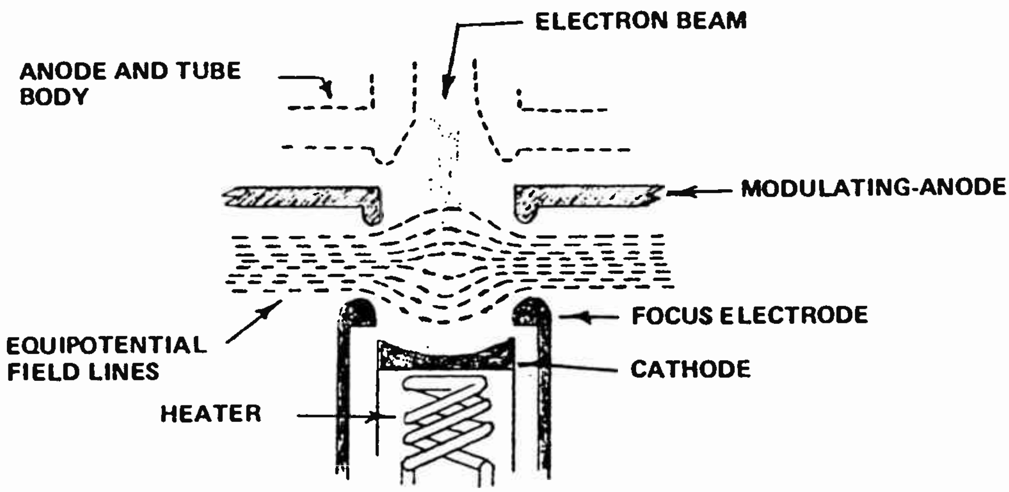


FIGURE 28 BEAM FORMATION IN MOD-ANODE CONTROL ELECTRON GUN

The modulating-anode, also called a mod-anode or control-anode, is a separate element insulated from the cathode and body. It usually takes the shape of a cylindrical structure with an aperture in the center, is placed close to the cathode and focus electrode and is operated at a positive potential with respect to the cathode. The anode, which is part of the body, is also operated with a positive potential in this type of electron gun. The amount of current drawn from the cathode is determined by the voltage applied between the cathode and mod-anode. Figure 29 illustrates a typical electron gun with a mod-anode that is used on various integral-cavity UHF-TV klystrons. Figure 30 shows a completed mod-anode control electron gun assembly and the anode/polepiece of the klystron body.

The operation of this electron gun is similar to the basic cathode control gun previously described, but, with the addition of a modulating-anode, it now has the capability of controlling how many electrons are drawn from the cathode by merely changing the cathode to mod-anode voltage, while the cathode to body voltage remains constant. The mod-anode controls the current in the klystron much like the grid in a conventional gridded vacuum tube.

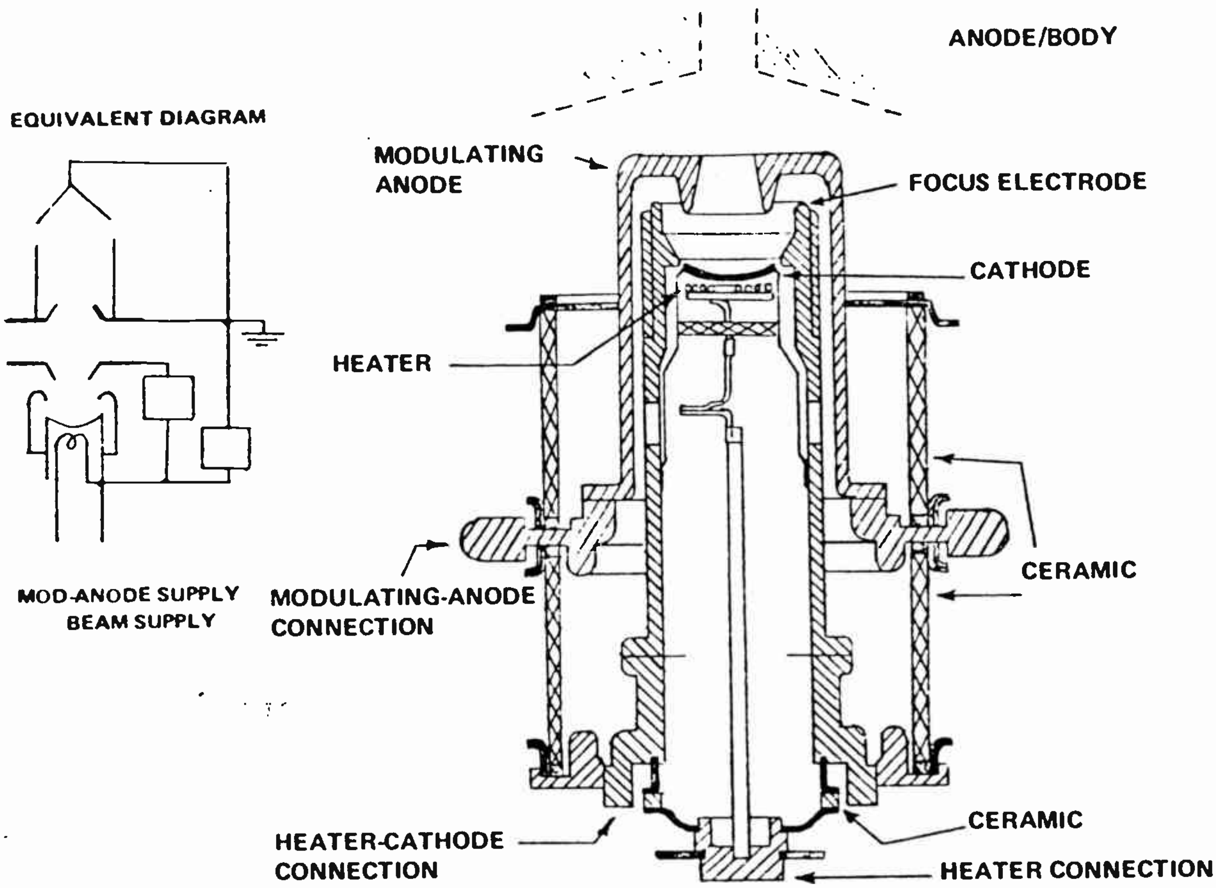


FIGURE 29: TYPICAL ELECTRON GUN FOR AN INTERNAL CAVITY TV KLYSTRON. HEATER AND CATHODE CONNECTIONS REMOVED

For full ON operation (full current), the voltage on the mod-anode must be the same as the cathode-to-body voltage. For operation at less current, the voltage between the mod-anode and cathode is lowered to some value less than that of the cathode-to-body voltage.

For example, if the cathode to body voltage were 20KVDC and the cathode to mod-anode voltage were 20KVDC (refer to the equivalent circuit of Figure 29), the tube would be drawing full current for the design of that particular electron gun and tube. Now, if the cathode to body voltage were left at 20KVDC but the mod-anode to cathode voltage were lowered to 16 or 17 KVDC, the tube would draw less current.

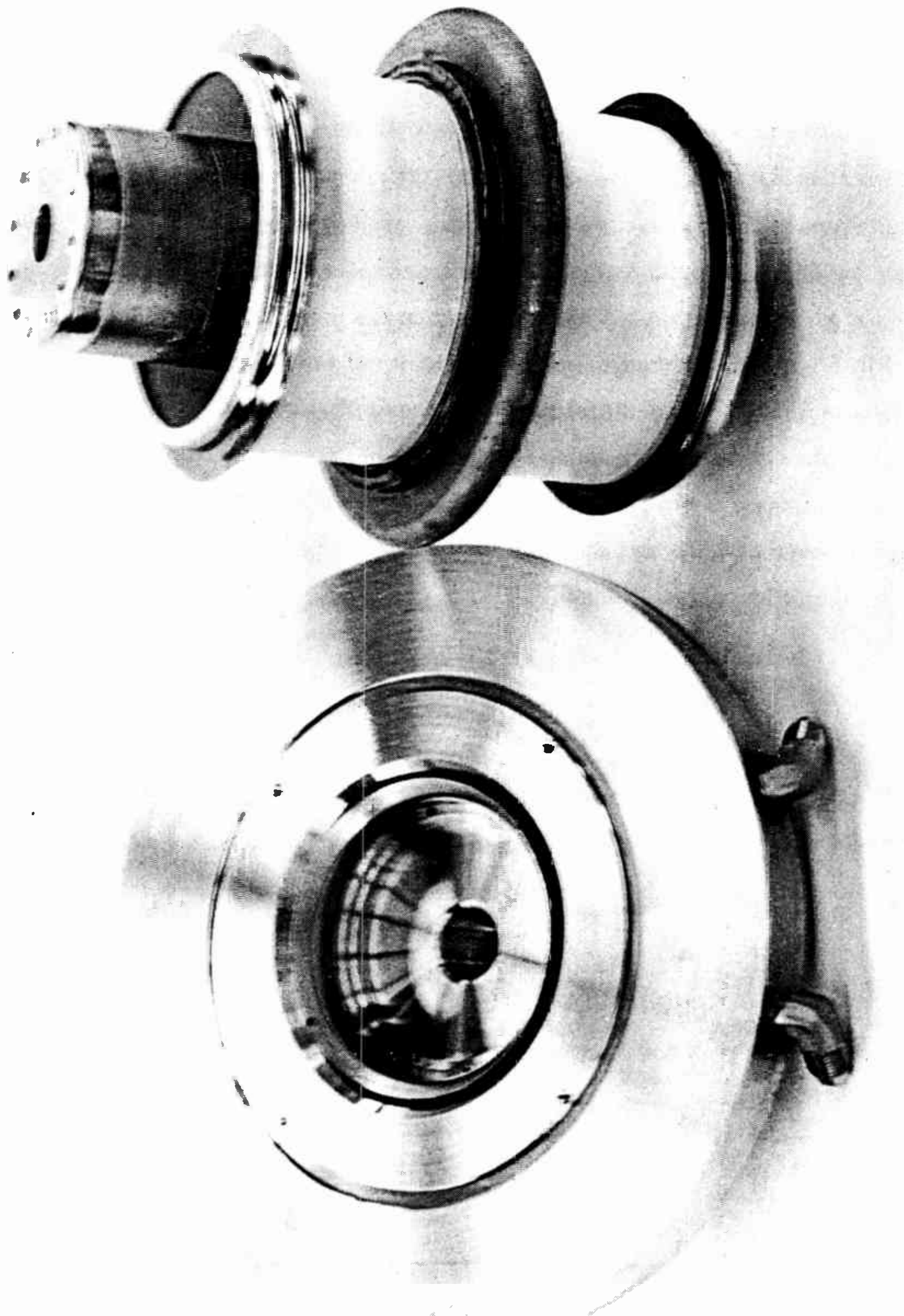


FIGURE 30: MOD-ANODE CONTROL ELECTRON GUN ASSEMBLY, AND ACCELERATING ANODE POLE PIECE
Photo courtesy of Varian Associates Inc.

With two different voltages influencing the electrons, there are, in essence, two regions of different electron velocities (see Figure 31). In other words, the electrons that are emitted from the cathode are initially drawn toward the positive potential of the mod-anode (Region I). The number of electrons and their velocity is dependent upon the applied mod-anode voltage. The area between the mod-anode and the anode (accelerating-anode) is Region II and changes only the velocity of the electrons available as the positive potential applied to the accelerating-anode does not affect the condition at the emitting surface of the cathode or the number of electrons that are emitted (see Figure 31). However, the voltage difference between the mod-anode and accelerating anode (or total voltage between cathode and accelerating anode), does affect the total beam power generated, by the following relationship:

$$(E_1 + E_2) I_b = \text{Total Beam Power}$$

Where

E_1 = voltage between the cathode and mod-anode

E_2 = voltage between the mod-anode and the accelerating anode

I_b = beam current generated by the cathode and mod-anode

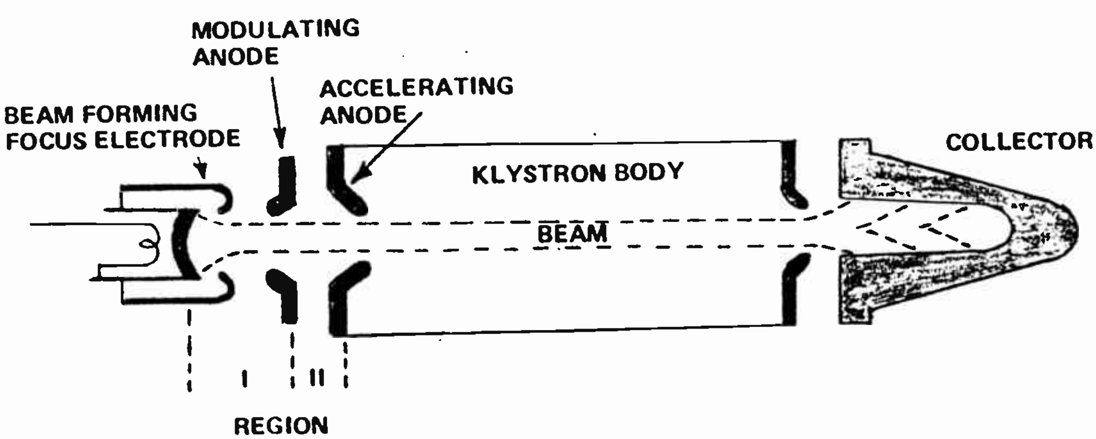


FIGURE 31: BEAM ACCELERATING REGIONS

The mod-anode control electron gun can also be used for pulse or modified pulse applications. In other words, the mod-anode can be switched from the negative cathode operating potential (cut-off) to approximately ground potential (positive to turn the tube ON), by using suitable pulse circuitry. The specific operating conditions for a given tube type would, of course, determine what voltage the mod-anode would be switched to. In this condition the full electron beam passes through the mod-anode with very little interception.

The tube can be turned OFF if the mod-anode is returned to the negative cathode potential. The full beam current must be switched again, but since the mod-anode interception is typically less than 1% of the beam current, the power requirements to switch the beam are greatly reduced. This system can be used for either pulse or continuous (cw) operation, and is an ideal system to use for video pulse operation. Figure 32 illustrates a simplified pulse system diagram.

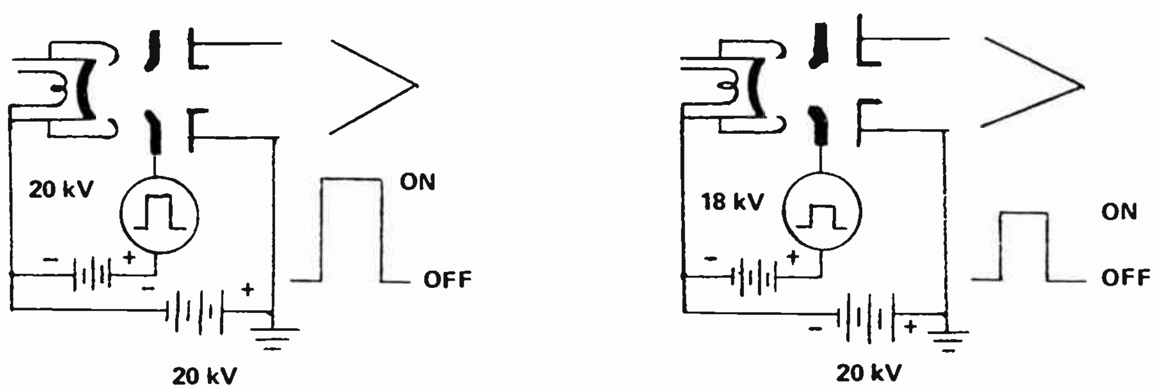


FIGURE 32: ANODE CONTROL (PULSE) ELECTRON GUN

3.7 Electron Guns for UHF-TV Klystrons

In the preceding sections, the fundamental operation of electron guns was covered including operation with a modulating-anode, which most all UHF-TV klystrons use.

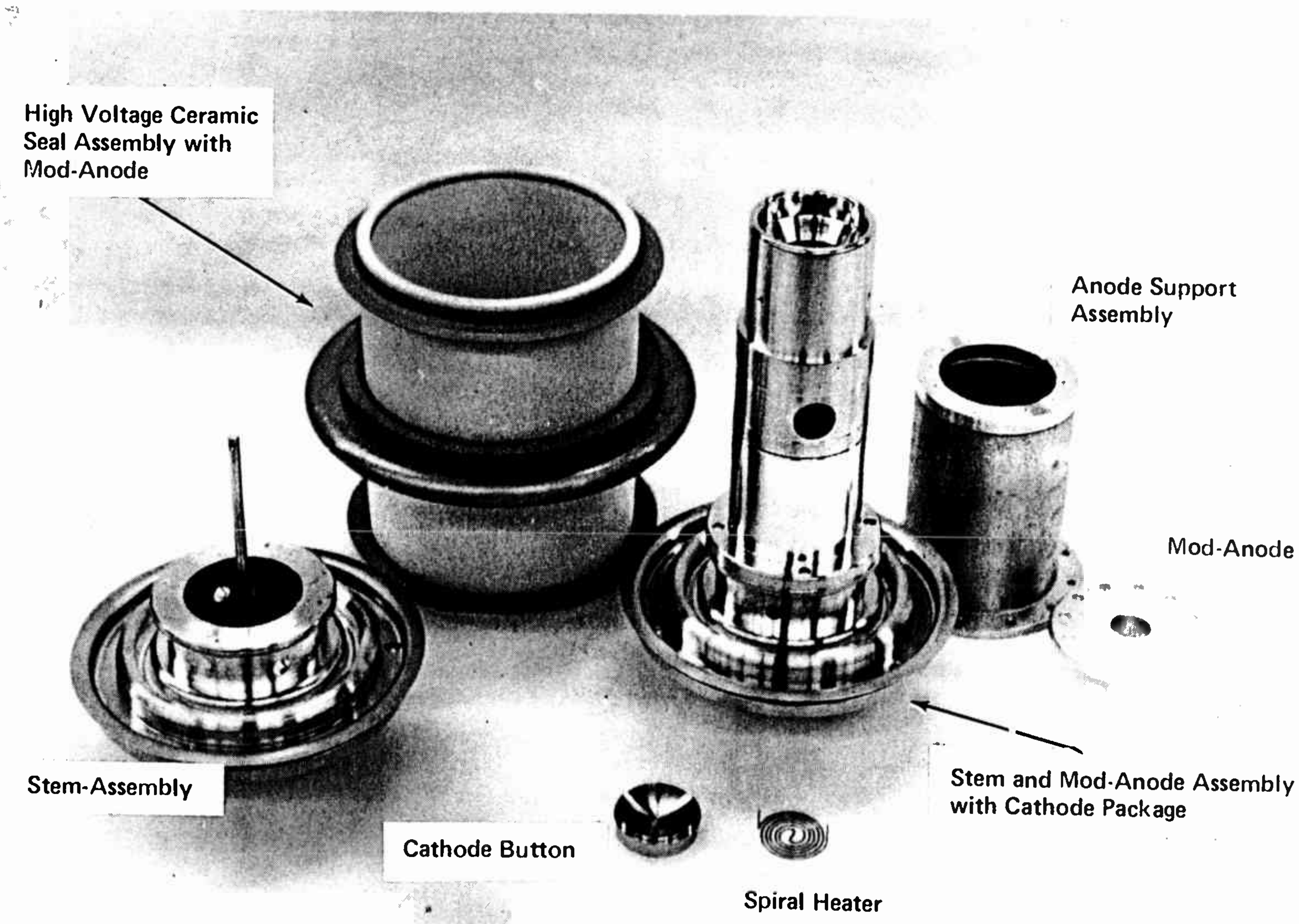
We can see from the photos of Figures 4 and 5 that each type of TV klystron (internal and external cavity) uses a different kind of electron gun to accomplish the same end result. The relative merits of each type are not important, but it is useful to know how two kinds of these electron guns are constructed.

First, let us consider the internal cavity klystrons that are available. Neglecting some slight differences between manufacturers, basically they are all constructed about the same. Figure 33 is a photograph of different assemblies and sub-assemblies prior to final assembly. This is the same electron gun shown earlier in Figure 30. Each of the major areas are labeled for identification.

The heater shown is uncoated tungsten, wound as a flat spiral. The cathode is an impregnated variety previously described. The heater is positioned close to the back of the cathode button with insulating spacers and heat shields. The center support rod shown on the base sub-assembly is the center heater lead. The contour of the focus electrode can be seen, with a small portion of the cathode surface just showing. The cathode is connected internally within the subassembly to the focus electrode as is one side of the heater, making the heater/cathode connection. (Refer also to Figure 29.)

The top of the modulating-anode is shown disassembled from the cylinder portion that is positioned over the focus electrode. This subassembly is then mounted inside the ceramic assembly shown, making connection at the center ring surrounding the ceramic for the mod-anode connection. The heater/cathode focus electrode sub-assembly fits in from the bottom of the ceramic and is sealed in position relative to the modulating-anode. The completed electron gun is shown in Figure 34. The mounting surface that determines the spacing of the modulating-anode to the accelerating anode is labeled in the photo. Refer also to Figure 30 for a view of the anode/polepiece of the body showing the mounting surface for the electron gun.

FIGURE 33: ELECTRON GUN SUB-ASSEMBLIES FOR INTERNAL CAVITY KLYSTRON
Photo Courtesy of Varian Associates Inc.



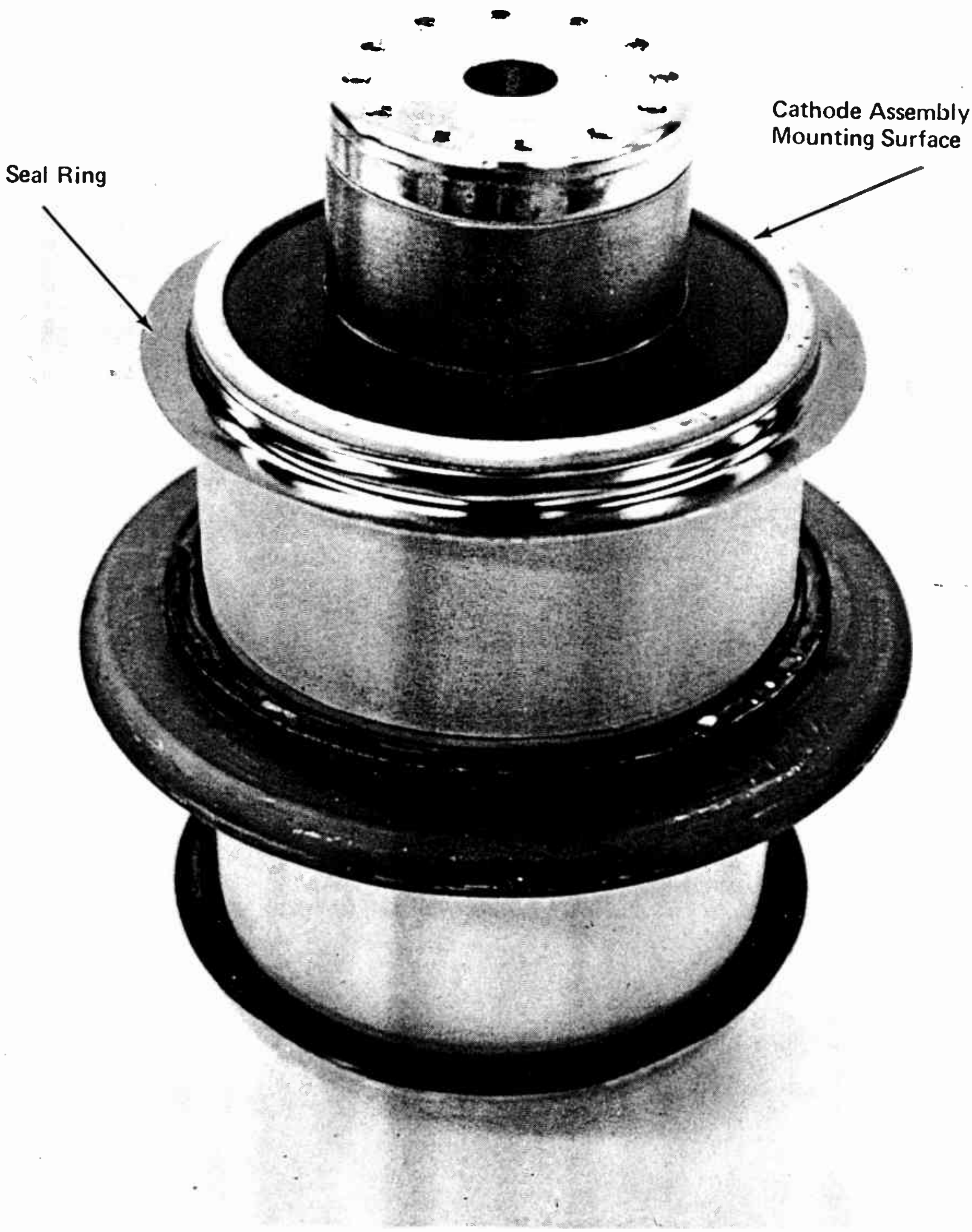


FIGURE 34: MOD-ANODE CONTROL ELECTRON GUN ASSEMBLY
Photo courtesy of Varian Associates Inc.

Now, let us examine an electron gun used with an external cavity type klystron. This electron gun is functionally the same as the one just described for the internal-cavity klystron. While the physical differences are apparent and the design for beam optics is different, but the fundamental operating principles are the same. Figure 35 illustrates a typical electron gun of this type showing some of the internal parts.

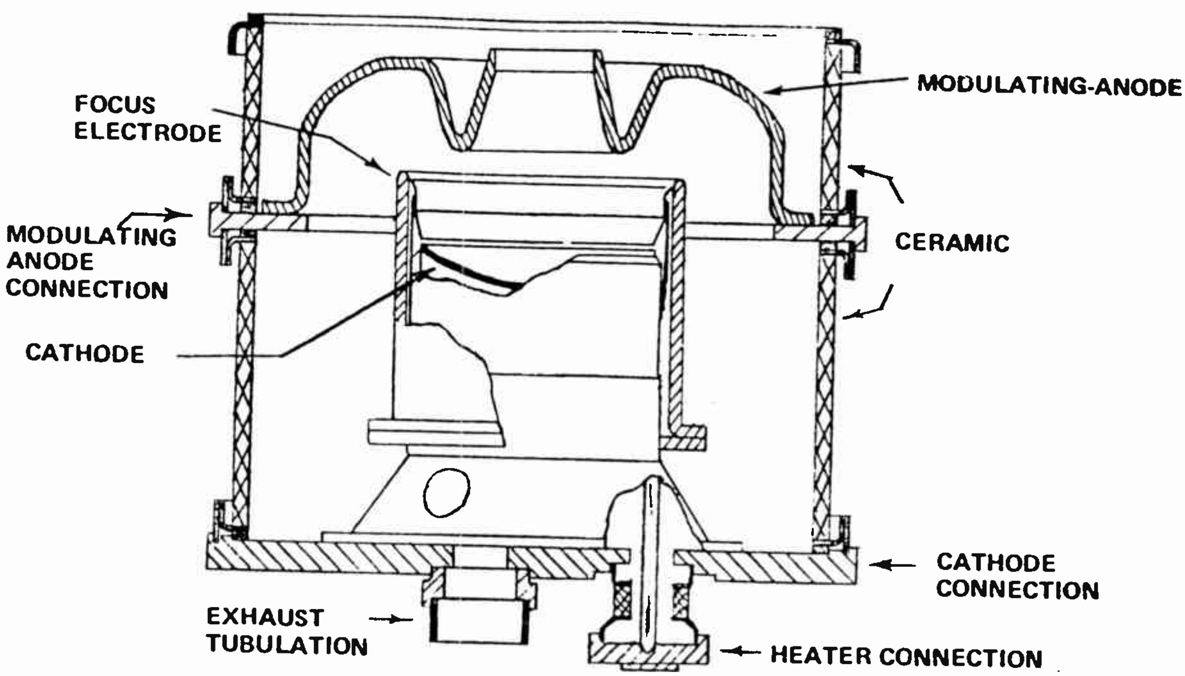


FIGURE 35: TYPICAL ELECTRON GUN FOR AN EXTERNAL CAVITY TV KLYSTRON

Figure 36 is a photograph of the assemblies and subassemblies prior to final assembly, with each part labeled for identification. The heater used with this electron gun is a coated tungsten wire wound into a flat spiral, and the cathode is a matrix variety emitting surface. The heater is positioned behind the cathode with insulating spacers and heat shield similar to the other electron gun described in Figure 33 and 34. The focus electrode is positioned above the cathode surface and as you can see it has a much larger aperture as compared to the previous electron gun described. The modulating-anode for this electron gun is considerable larger and mounts inside the ceramic assembly at the center ring which is the external connection. The heater and cathode

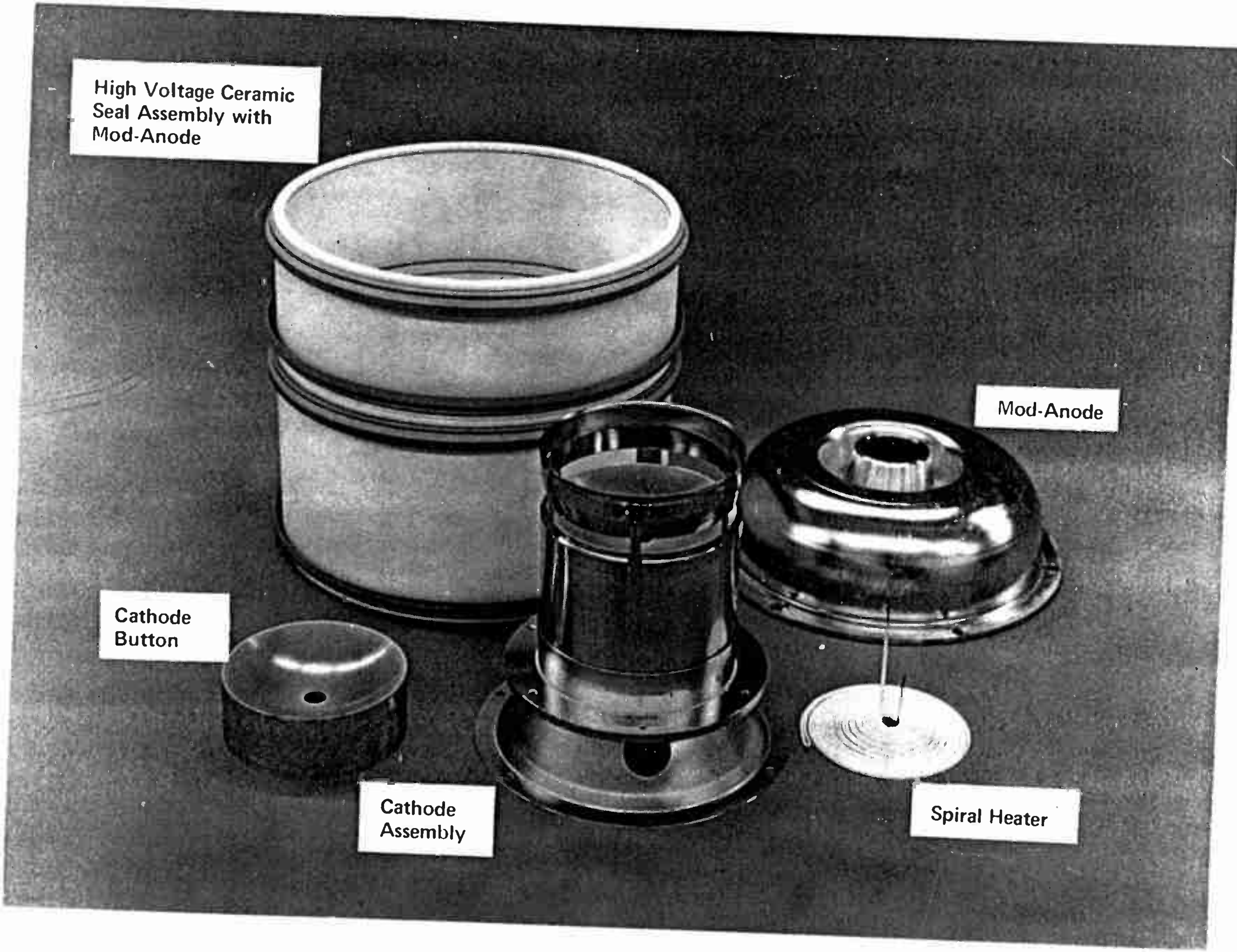


FIGURE 36: ELECTRON GUN SUB-ASSEMBLIES FOR EXTERNAL CAVITY KLYSTRON
Photo courtesy of Varian Associates Inc.

are also connected internally within the cathode/focus electrode structure to make the heater/cathode lead.

The completed electron gun assembly is shown in two photographs. Figure 37 shows the base end with the heater/cathode connections and the getter connection. Figure 38 shows the completed electron gun from the cathode and mod-anode side.

Both of the electron guns just described require a certain amount of air cooling during operation and it is highly important to make sure that the ceramics are clean, in order to reduce the possibility of external arcing, which could puncture a seal.

Though very strong ceramic-to-metal seals are made with a metalizing material only a few thousandths of an inch thick, the energy contained in a sustained arc is as powerful as some arc welders, and can blow a hole in the seal or mounting flange if not arrested.

FIGURE 37: MOD-ANODE CONTROL ELECTRON GUN ASSEMBLY
FOR EXTERNAL CAVITY KLYSTRON
Photo courtesy of Varian Associates Inc.

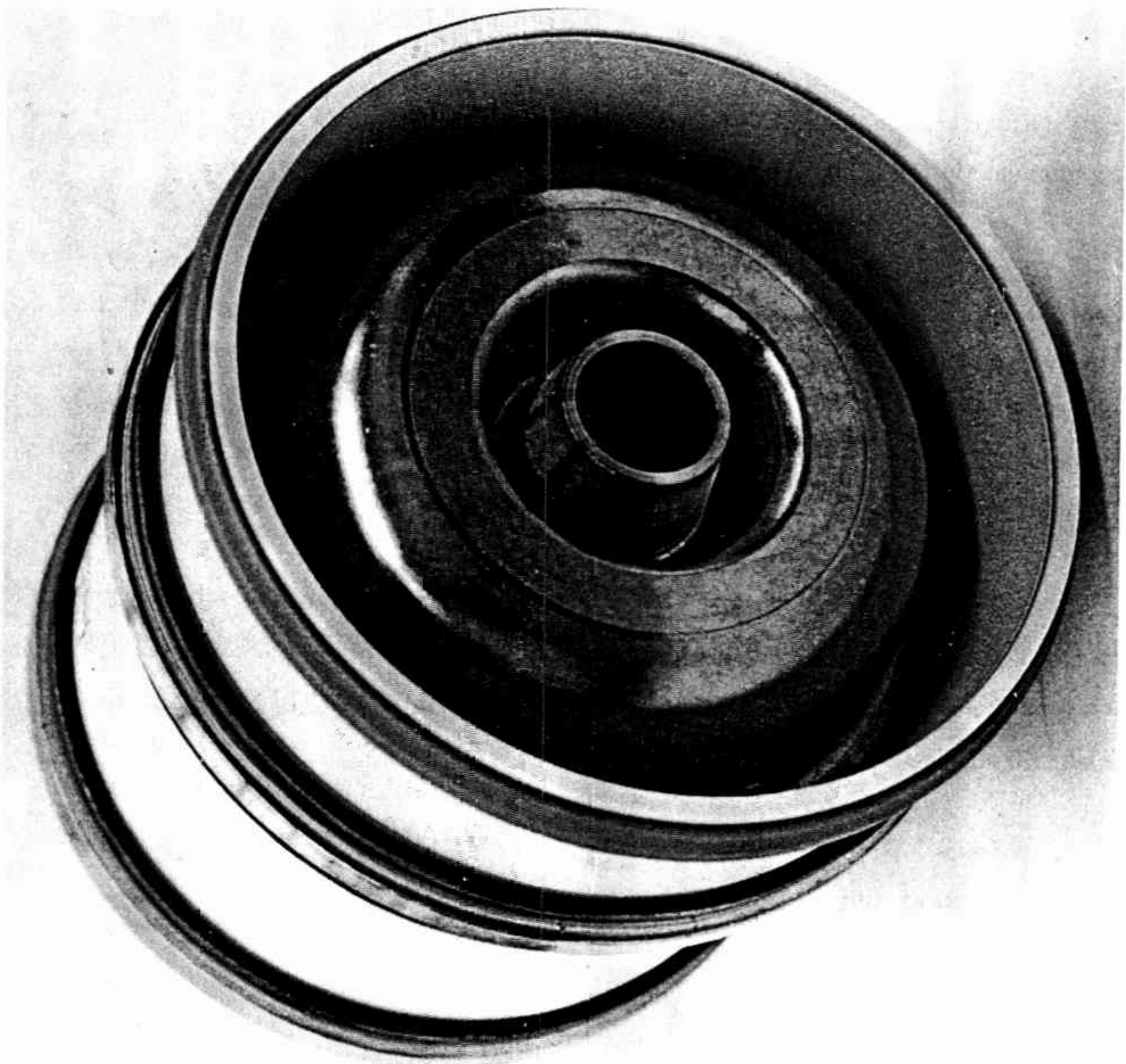


FIGURE 38: TOP VIEW OF MOD-ANODE CONTROL ELECTRON GUN ASSEMBLY FOR EXTERNAL CAVITY KLYSTRON
Photo courtesy of Varian Associates Inc.

4. MAGNETS AND MAGNETIC FIELD

Though not considered as one of the three basic sections of a klystron, the magnet and magnetic field are very important to the operation of a klystron amplifier.

Magnets are placed around klystrons, or any similar microwave device, in order to confine or maintain the size of the electron beam and keep it aligned with the inside of the tube for proper interaction with the rf section as the electrons travel from the cathode to the collector. Without the magnetic field, the beam that is formed at the cathode will expand at a rapid rate once it passes the anode. This expansion of the beam without the magnetic field is due to the mutual repulsion among the negative electrons.

Magnetic fields may be developed by one or more electromagnet coils or by permanent magnets. The various configurations of these two basic methods can produce what is called straight fields or reverse fields. There are also electro-static-focused klystrons (ESFK), that are used for special applications where no magnets are used. The focusing of the beam along the complete axis of such a tube is accomplished in a manner similar to the electrostatic lens focusing which we discussed earlier in the section on electron guns.

Straight fields are produced by either solenoids (electromagnets) or by combinations of permanent magnets and polepieces arranged to produce a uniform field parallel to the axis of the beam (see Figure 39).

Reverse fields are produced by periodic-permanent magnets (PPM). The magnets are arranged so as to produce a field that periodically reverses in direction. This system is based on the fact that the action of the longitudinal magnetic field along the axis of the electron beam depends only on the magnitude of the field, and not on its direction. This is an ideal system where weight and size are a factor, as with traveling wave tubes[4]. Inasmuch as this discussion is primarily concerned with basic concepts related to UHF-TV klystrons, only the operation of electromagnets with straight field will be covered.

The straight field (also called axial field) produced by an electromagnet is illustrated in Figure 39. You will note that the typical field plot of "Gauss" is flat. There are, however, some klystrons that require a slightly tapered field with more field strength at the collector end of the tube. This is due in part to the greater density of the electrons (during rf operation) at the output end of the tube which require a greater magnetic field to confine them.

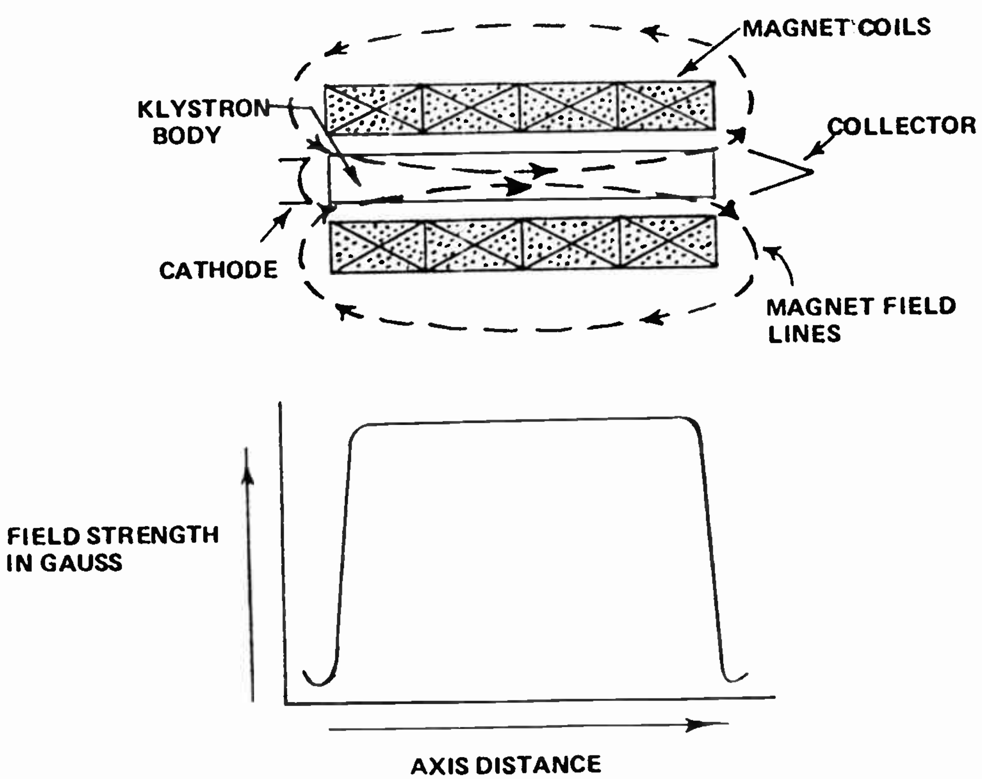


FIGURE 39: TYPICAL ELECTROMAGNET STRAIGHT FIELD

[4] Refer to "Practical Theory and Operation of Traveling Wave Tubes" by Reginald D Perkins, R and L Technical Publishers, San Jose, California, November 1973, Revised May 1977.

Electromagnets are made up of one or more coils, depending on the design and application. The strength of the magnetic field produced is controlled by changing the current flow through the coil, and the shape of the field is determined by polepiece geometry and winding distribution inside the coil.

Figure 40 illustrates an electromagnet with the various components marked along with the magnetic field path developed. The magnetic field path is somewhat exaggerated for explanation purposes. Actually it enters and leaves through the polepieces with fringing fields outside these regions. Figure 41 pictures a similar magnet with an external cavity UHF communications tube installed.

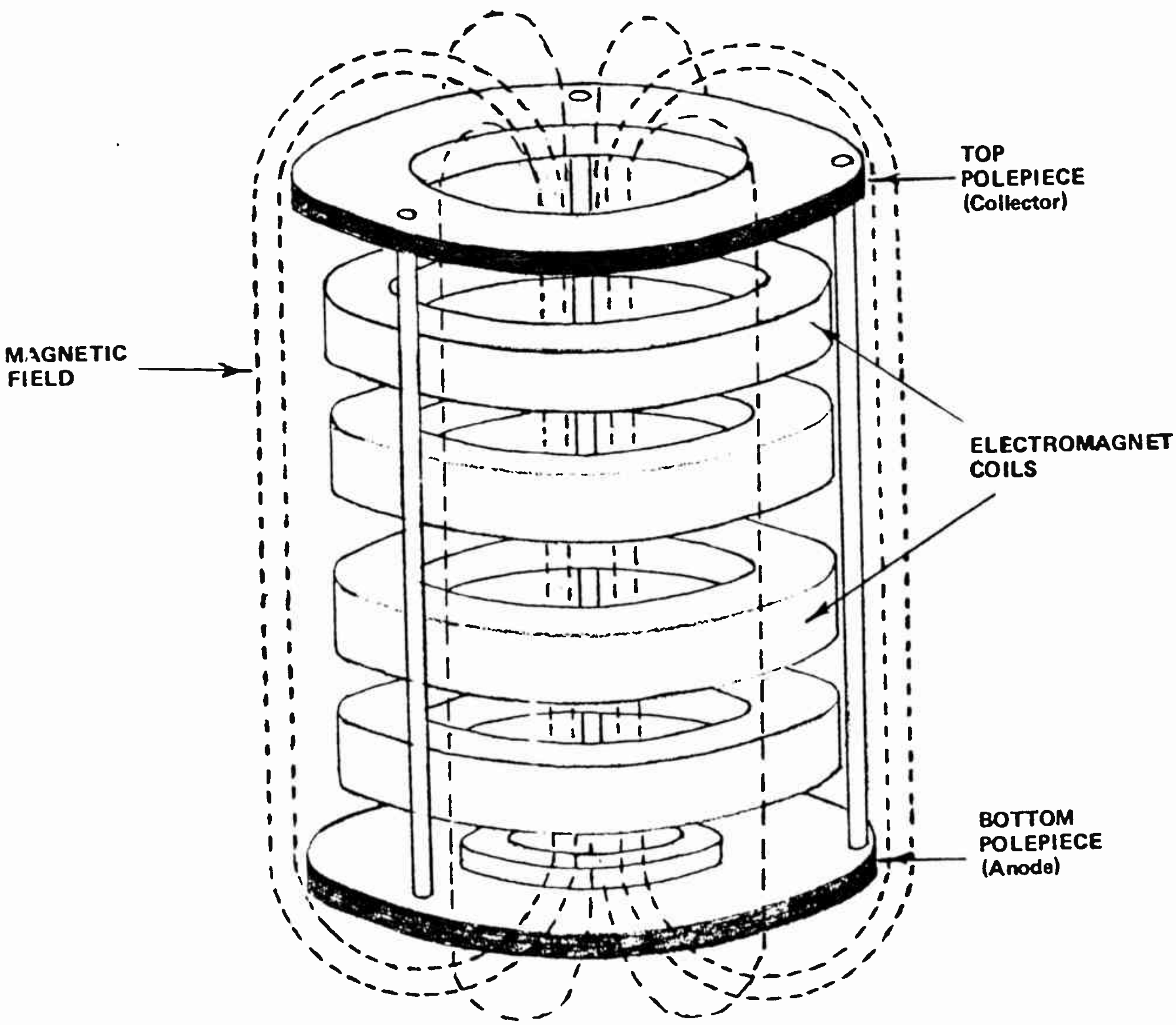


FIGURE 40 : BASIC ELECTROMAGNETIC COMPONENTS AND FIELD

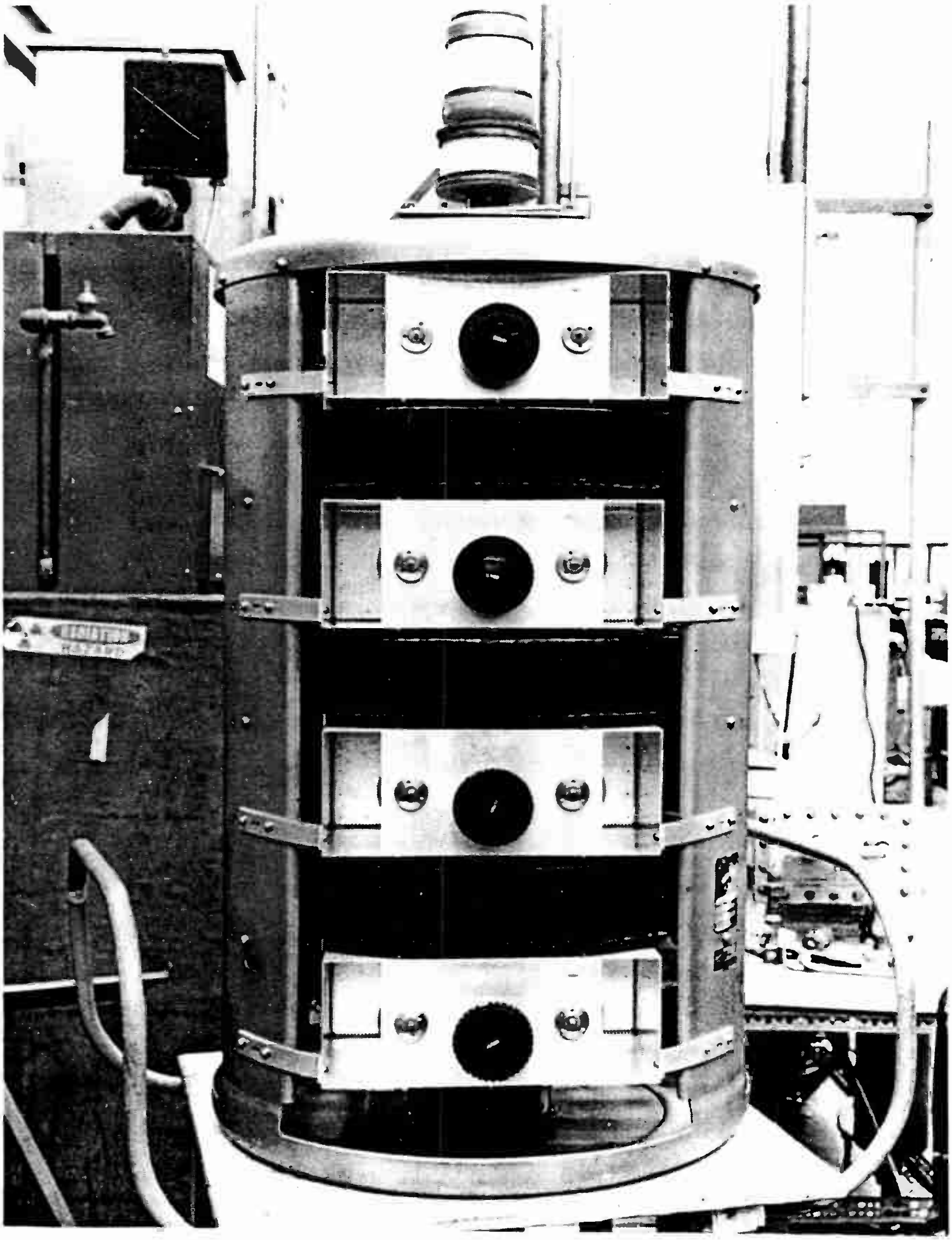


FIGURE 41: UHF COMMUNICATION TUBE AND ELECTROMAGNET
Photo courtesy of Varian Associates Inc.

There are many klystron amplifiers that use only one electromagnet and, therefore, require only one power supply, while others may have as many as six coils and require a power supply for each coil. Some of these multi-coil and power supply systems are designed to operate from a single control, while others are made individually adjustable to permit variation of the field strength along the length of the klystron. It is especially desirable in this case that each individual coil be provided with an individual ammeter. In all cases, the controls must be capable of smooth, continuous adjustment.

The dc supplies that are used with electromagnets are usually fairly simple with conventional rectifying techniques. However, it is important to have the supply well filtered so that the output current contains only a relatively small ripple current. The supplies should be filtered for about 5% or less if minimum noise output is to be obtained. Ripple on the dc magnet current may cause the electron beam to "wander" slightly, at the ripple frequency. This can cause noise in the form of undersirable amplitude and phase modulation of the rf output signal.

Inadequate filtering or no filtering of the magnet power supply may cause other additional problems. Rectifiers may create large spikes on the rectified voltage, which is also a source of noise. The lack or absence of filtering may also cause protection problems in some interlock systems. For example, if a voltage transient or primary voltage fluctuation has caused the magnet supply to shut down, the body over-current interlocks would normally shut the high voltage off to protect the klystron. With the lack of filtering, the magnet supply decay time may be too fast for the other protection circuits to protect the klystron. With this fast decay in magnet current, the beam will spread just enough to damage or destroy the tube permanently. The manufacturer of the equipment and/or klystron should be consulted regarding filtering and response times of the protection circuits for shutdown of the beam voltage.

Figure 42 illustrates the beam forming action of the electromagnet where the magnetic field is developed between two cylindrical plates called polepieces. The size, shape, and position of these two polepieces is important in shaping the magnetic field. It is also important for the klystron to seat properly in any given magnet structure, without forcing, as the magnetic field enters and exits through the polepieces.

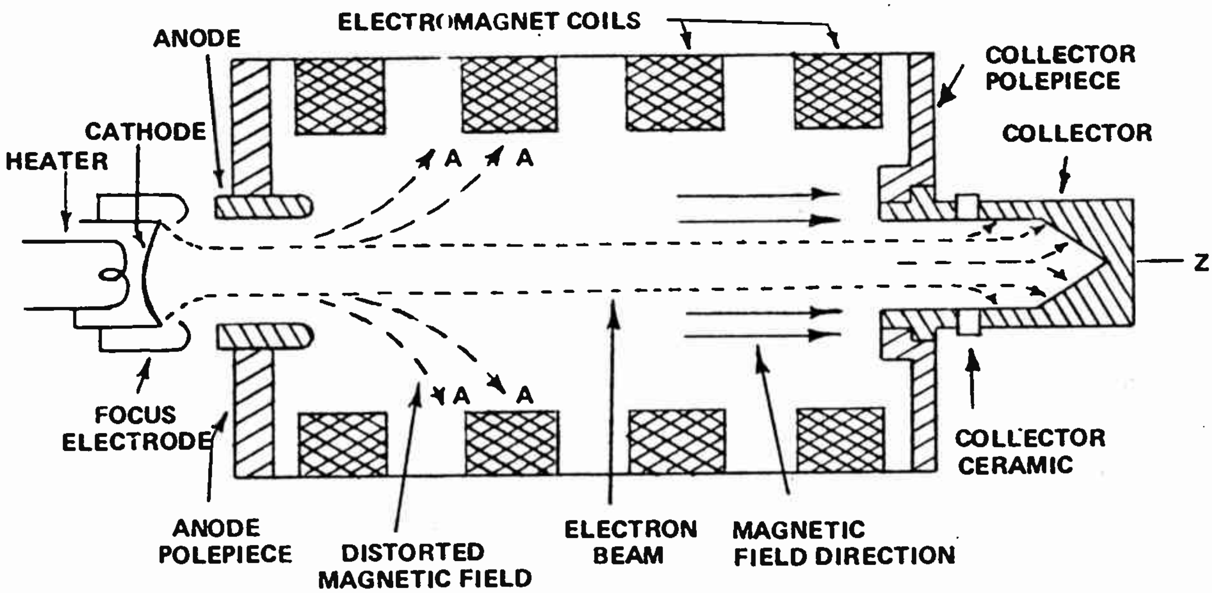


FIGURE 42: BEAM ACTION IN THE MAGNETIC FIELD

There are two beam path examples shown in the Illustration of Figure 42; one shows the beam confined so the diameter is the same all the way through the klystron (Z axis) and the other is an exaggerated example of the beam spreading out to points AA.

The confined beam is the result of an adequate magnetic field present between the anode and collector polepiece. The beam path that is spreading out to points AA, is the result of a complete lack of magnetic field, and would, of course, completely destroy the tube.

Other points could also be shown which would spread out less than points AA (based on an A to Z scale) indicating other magnetic field strengths between zero and normal operation. However, any field strength that does not maintain the beam at a size where it will clear the rf structure will have taken some similar path toward points AA. Consequently, all magnetic structures for klystrons must meet the following requirements:

(1) The magnetic field along the rf structure must be strong enough to confine the beam to the proper size.

(2) The magnetic field lines must be parallel to the axis of the electron beam and drift tubes in the rf structure, so the electron beam will travel down the drift tubes in a straight line.

Even with an adequate magnetic field, some electrons will go "astray" and will not remain in the main electron beam. These electrons will be intercepted by the klystron anode or drift tubes. In high-power klystrons it is particularly important to minimize the number of these stray electrons because they generate heat when they strike the drift tubes. Heating can be a severe problem in high-power klystrons because drift tubes are often difficult to cool. Temperatures can become high enough to melt the metal in the drift tubes and destroy the tube, and it only takes a few milliseconds of stray electrons or distorted beam to do such damage.

Don't be misled into thinking that all you need to do is increase the magnetic field to reduce the beam diameter, resulting in a lower body current, and that then the klystron will operate correctly. If the electron beam has a very small diameter compared to the size of the drift tubes, the beam does not "couple" strongly to the drift tube gaps and, therefore, it does not react strongly enough with the klystron cavity, which results in lower power output. There can also be another side effect from having a beam diameter too small, -- the beam can be so concentrated as to cause hot spots in the collector, resulting in an overtemperature condition.

The performance of a klystron amplifier can sometimes be improved by permitting the electron beam to be as large as possible, while still keeping the body current below the maximum specified for the tube. The size of the electron beam can, to some extent, be controlled by the magnetic field and, therefore, performance can sometimes be improved by adjusting the magnetic field in a way which does not necessarily result in the minimum body current; but where the beam shape is somewhat larger than the minimum obtainable, it may result in slightly more power output. On some klystrons this could be as much as 5 percent more power. Here again, before attempting this maneuver, the manufacturer should be consulted, as these design parameters may have already been taken into account in the operating conditions. Another point to remember regarding magnetic field and body current: body current usually increases with rf applied to the klystron, which should be expected since rf causes the electron bunches to form. The dense negative electron concentration in the bunches causes the electrons to further repel each other, and the diameter of the bunches may then become larger than the diameter of the beam without the bunches. Consequently, some of the electrons in the bunches may be lost to the drift tubes as previously mentioned, and the body current will increase.

A larger change in magnetic field often requires a retuning of some klystrons if peak performance is expected. Here again, this maneuver also should not be done without consulting the particular manufacturer of the klystron or if the tube specification sheet supplied by the manufacturer so states that this is permissible or necessary.

All electromagnet coils must establish their fields in the same direction. This is especially critical where more than one coil is used in the electromagnet. On electromagnets that have the voltage terminals marked as top and bottom coils or plus and minus (+ and -), careful observance of polarity should assure correct field polarities. Polarity connections can even be critical in single coil magnets, where winding distribution may be just enough to change the basic operating parameter. Figure 43A is a simplified illustration of the normal field and beam for a properly adjusted magnet, while Figure 43B illustrates a case where a coil of a multicoil magnet is physically reversed or the polarity of the current has been reversed. A damaged or burn out coil would also give you basically the same effect as Figure 43B.

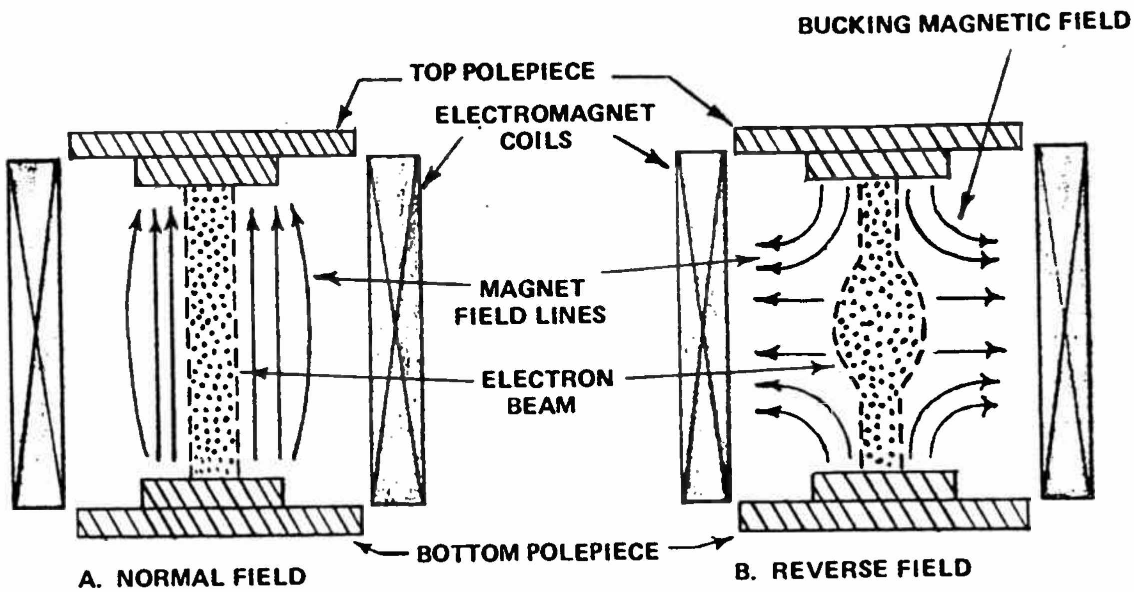


FIGURE 43 : NORMAL AND REVERSE MAGNETIC FIELDS

The example of Figure 43B can easily happen when coils have been replaced in the field by inexperienced personnel. The coil has either been physically positioned upside-down or the polarity connections have been reversed, resulting in a repelling magnetic field and a bulge in the beam. This bulging will cause the beam to strike the drift tubes or at either end of the tube if one of the other coils is the problem. Therefore, it is important that the magnet coils are installed and connected properly before using.

A simple way to check that electromagnets with straight field are all working and do not have a bucking field, is to hold a metal object e.g., a screwdriver, in your hand so that it is horizontal, and moving it slowly down through the center of the magnetic field while the tube is out of the socket. There will be constant torque on the metal screwdriver, and, if there is a bucking field, the screwdriver will want to rotate in another direction. If the field is inoperative at one area, there will be a reduction of the force on the screwdriver.

This simple field test will not tell you if you have a magnet that has been damaged, or is susceptible to arcing, yet apparently still operative, or is mounted with a tilt to the field. Is is only a quick field check to determine a bucking field or a dead area.

Properly adjusted electromagnets, whether single coil or multi-coil, can also have the magnetic field distorted by small magnetic metal objects, objects as small as a 10-32 size nut or bolt, that may have become attached to the tube or magnet when the magnet was energized. The electrons in the beam will follow the distorted magnetic field at the position of the foreign object and most likely will strike the walls of the drift tubes. Figure 44 illustrates this condition.

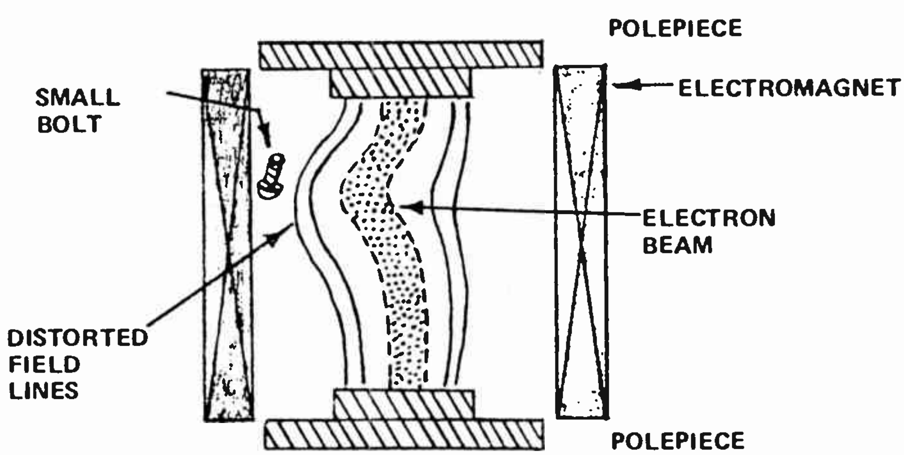


FIGURE 44 : EFFECTS OF PERTURBATING MATERIAL IN MAGNETIC FIELD

All electromagnets require either forced air or liquid cooling. Without adequate cooling, the electrical resistance of the coils will cause heating when an electrical current is passed through them. All magnet coils are designed to operate at some elevated temperature, and, if the coils get hotter than the design parameters, the electrical resistance of the coils will increase and the current in each coil will drop. This in turn will cause the magnetic field strength across the klystron to weaken, for the strength of the magnetic field is directly related to the amount of current flowing through the coils. Overheating of the coils can also cause permanent damage to the insulation between the turns of the coils and between the coils and ground, causing a short to occur. If a short does occur, the current read on the meter in the system will not be representative of the strength of the field, for a short will always weaken the magnetic field. It is advisable to also check the voltage across each coil to make sure that it is working properly.

If the cooling is in the form of forced air, the entrance and exit of the air must be clear and free of obstructions. Air cooling systems that utilize enclosure shrouds will, over a period of time, collect dirt and moisture from the surrounding air if the room is not well filtered, which is usually the case. For this reason, periodic cleaning of the air path is advisable.

Liquid cooling systems, whether they are complete closed systems or open-drain systems, should also be periodically checked to make sure they are clear of dirt or excessive mineral deposits and the magnet cooling lines are open and free of any obstructions causing a lack of liquid coolant flow or restricted coolant flow.

The following precautions should be observed at all times regarding the use of electromagnets:

1. The klystron must be placed in the magnet assembly carefully so that no damage occurs from hitting, bending, etc.

2. There must always be an adequate amount of current flowing through the coils so the klystron is not damaged by a weak magnetic field.

3. Magnetic materials such as wrenches, bolts, or nuts must not be left inside the magnet assembly after installing the klystron.

4. All magnetic material in the areas surrounding the cathode and collector should be removed so that will not become attached when the magnetic field is turned on.

5. The direction of the magnetic field developed by each coil must be the same.

6. Magnetic tools must not be used to adjust the klystron while operating.

7. There must always be an adequate amount of cooling for the electromagnet coils.

5. RF STRUCTURE

In Section 1.2 and 2.1 we have shown how each element of a gridded tube e.g., a triode and its circuits are dependent on and associated by some common reference for operation. In the klystron, the three major sections and their functions are accomplished in three separate and well defined sections of the tube (beam generation, interaction and dissipation), each of which can be optimized in design independently of the others. The only dependence each section has on the other is that each must function properly in the total operation of the klystron. In this discussion of the rf structure, it will be assumed in all cases that there is a beam available when called for and that there is a way of dissipating the electron beam without showing power supply connections between each section.

Along with a general description of the klystron rf structure and how it functions, this section will also cover in detail an analogy of cavity resonator development, cavity tuning methods, how the cavities function through interaction with an electron beam. We have also shown how rf structures are built.

The rf sturcture of a klystron amplifier is composed of tunable resonant circuits (called cavities) and field-free drift spaces that are positioned along the axis of an electron beam. Physically, they are hollow, metal-walled chambers with means for admitting and extracting electromagnetic energy. Electric fields are developed across the capacitive component (gap) of the drift tubes when the electron beam encounters the first resonant cavity that has been excited by the signal frequency to be amplified. An rf structure is illustrated in a simplified drawing in Figure 45, and Figure 46 shows a more detailed sectional view of a typical UHF klystron rf sturcture. The illustration of Figure 45 is what I choose to call a basic klystron, consisting of a heater/cathode, rf structure and collector.

I am sure that many readers have seen numerous books or articles on klystron amplifiers that describe general klystron theory by implying that all klystrons are constructed with metal grids across the drift tube gaps in the rf resonant cavities. In many ways this is a kind of traditional approach to the fundamentals of klystrons,

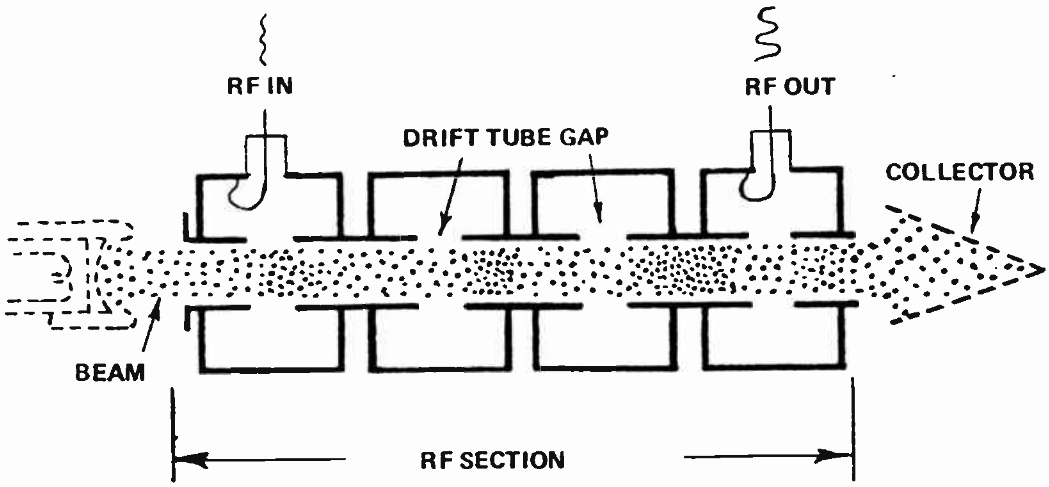


FIGURE 45: KLYSTRON RF SECTION

where the gridded gap is used for direct comparison to triode grids. Indeed, many low-power klystrons, such as the reflex klystron or smaller low-power amplifiers do use wire mesh or vaned-grids across the drift tube gaps. However, such grids on higher power tubes would intercept large amounts of the klystron beam, and, being very difficult to cool properly, the beam interception would cause the grids to melt, destroying the tube.

Eliminating the grid at the drift tube gap does not change the fundamental operating principles but it does have a secondary effect on the klystron performance. For example, in certain cases where the beam has a very small diameter compared to the size of the drift tubes, the beam will not couple strongly at the gaps and therefore it does not react strongly with the klystron cavity. Consequently, with the addition of the grids across the gaps, much smaller cathodes with small beam diameters can be made to work more efficiently through more effective coupling to the cavity.

Fortunately, by proper design, klystron amplifiers canbe made to work efficiently without actually having grid wires across the drift tube gaps. This is accomplished by having an electron beam as large as possible, while keeping the body current interception below the maximum specified or design value of the tube. This is an oversimplified answer, as the design of all klystrons is far more complicated than simply allowing the beam to be large for better interaction at the drift tube gaps.

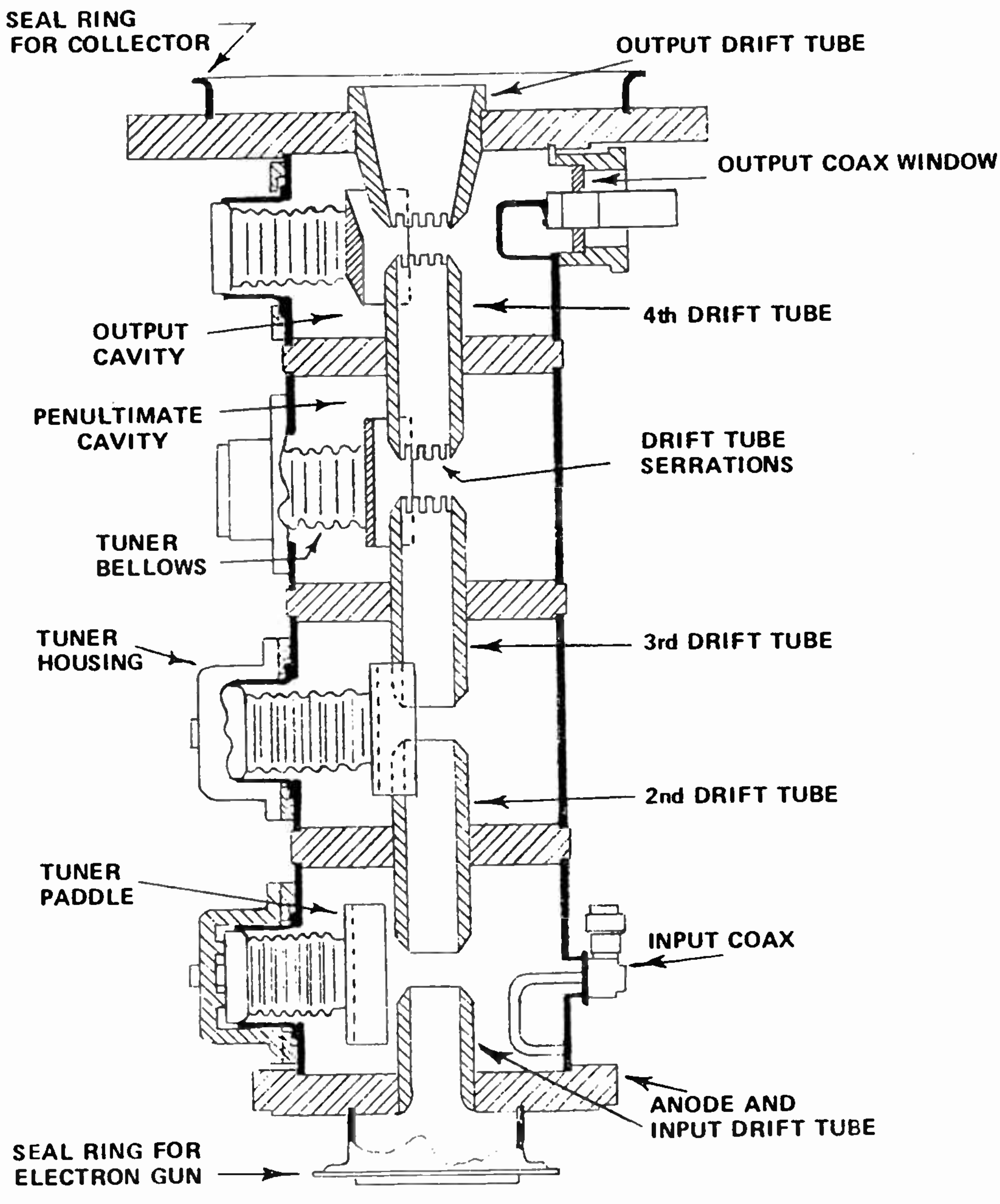


FIGURE 46: CUT AWAY VIEW OF INTERNAL CAVITY KLYSTRON

So that there will be no confusion during the discussion of rf structures, I will depart from the more traditional approach, and will describe all general theory of resonant cavities without gridded gaps, except for an historical account of early klystron design.

The drift spaces commonly called a drift tube, is an axial interrupted tube or cylinder that connects each cavity. There may be as many as two to six interruptions called gaps along the length of the klystron rf structure for a given design of klystron. Modern klystrons built for UHF-TV have either 4 or 5 cavities in the rf structure.

A resonant cavity is constructed so that it surrounds each drift tube gap and is arranged so that the ends of the drift tube sections protrude through the walls of the cavity. Figure 47 illustrates a cut-away view of a simple resonant cavity (shown without the tuning mechanism) and Figure 48 pictures an actual section of a UHF internal cavity klystron body, looking into two of the cavities showing the drift tubes.

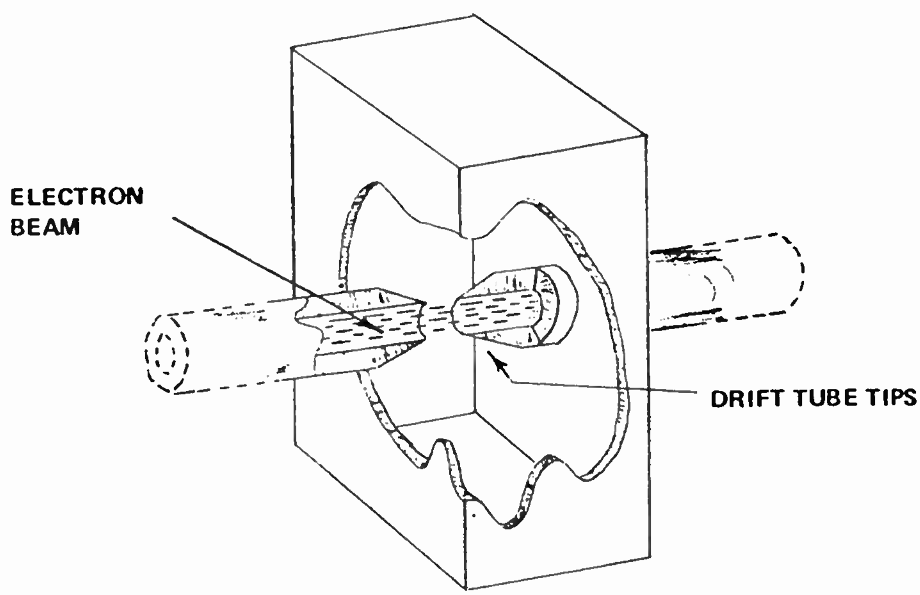


FIGURE 47 : TYPICAL RESONANT CAVITY

The drift-tube gap in a resonant cavity is roughly equivalent to the capacitor in a conventional low-frequency resonant circuit, in that alternating voltages at the rf frequency can be made to appear across the cavity gap. Circulating currents will flow between the two sides of the gap through the metal walls of the cavity when excited by an rf signal, similar to the flow of rf current in the inductance of an LC resonant circuit.

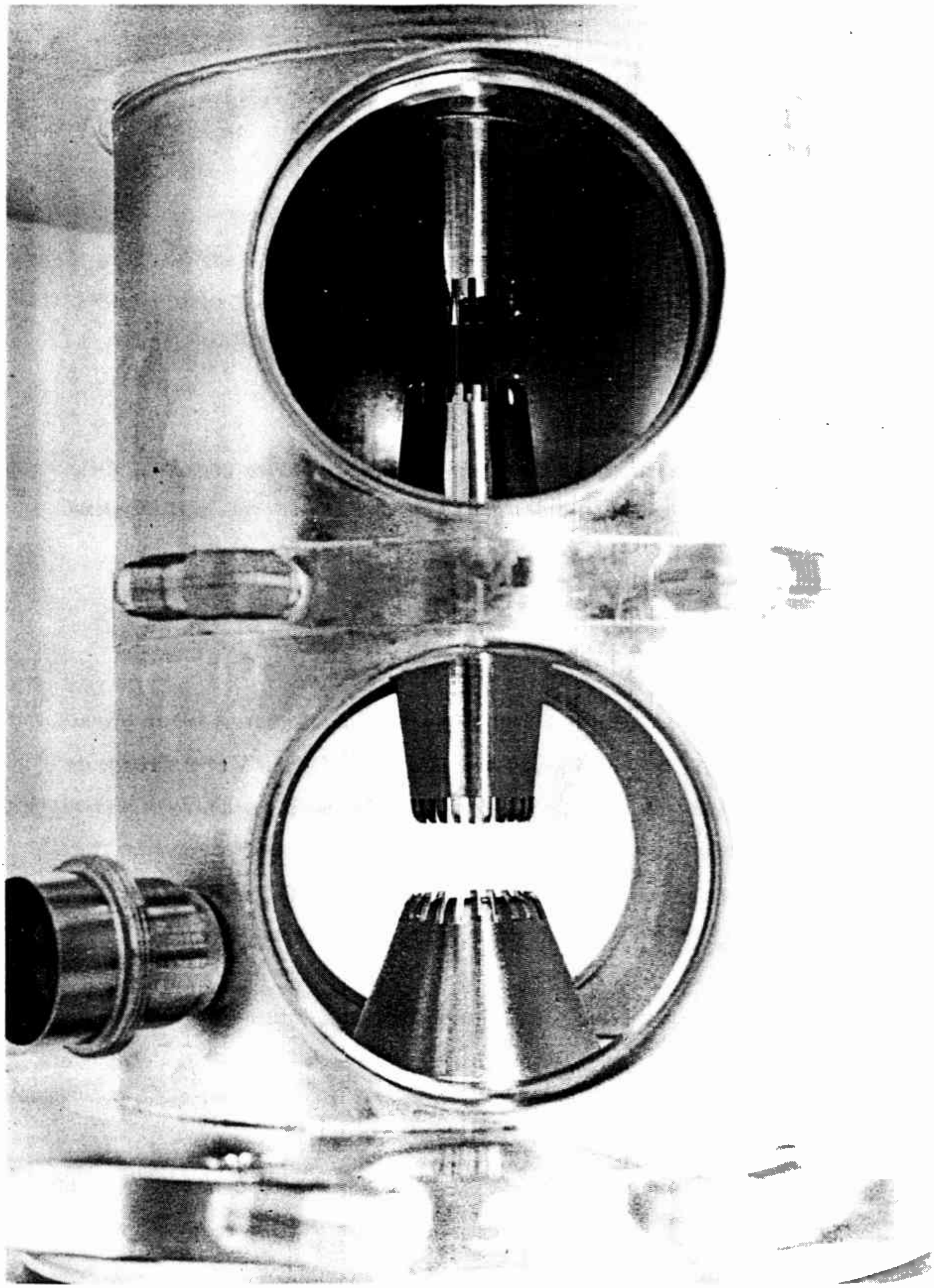


FIGURE 48: INTERNAL VIEW OF CAVITIES AND DRIFT TUBES
Photo courtesy of Varian Associates Inc.

As simple as this comparison may seem, one must not lose sight of the fact that in a triode, both ac and dc field components are present in the grid-plate space, and the electrons simultaneously receive energy from the dc field and deliver it to the ac field. In a klystron the two fields are separated. Electrons receive energy from the dc source in the accelerated motion between the cathode and the first drift tube, and part of this energy is delivered to the output cavity when electrons are decelerated by the fields in the output gap.

It should be clear then, that one must reorient one's thinking regarding operation of vacuum tubes when discussing klystron resonant cavities. We shall examine the resonant circuit in more detail as we proceed.

5.1 Cavity Resonator Development

There are numerous types and shapes of resonant cavities in use with present day microwave tubes. However, our discussion will be concerned with the resonant cavities called "re-entrant" cavities, and their function in the rf structure of a klystron amplifier. In construction, a re-entrant cavity resembles a concentric coaxial line at both ends with capacitive loading of the center conductor. The re-entrant cavity in one form or another is the basis of all klystron resonant circuits.

There are also two basic concepts of re-entrant rf structures that are used with various types of klystrons which include klystron amplifiers for UHF-TV. They are the internal and external variety. This means that the internal cavity concept uses the cavity structure and walls as part of the vacuum seal of the klystron body, similar to the one pictured in Figure 48. The external cavity concept is demountable tuning cavities that are assembled around the drift tube gaps and cylindrical ceramic envelope sections (or windows) which are part of the vacuum seal (see Figure 49). These two different approaches to tube and cavity design do not affect the basic operation of the rf structure, which should be evident as you proceed through the text.

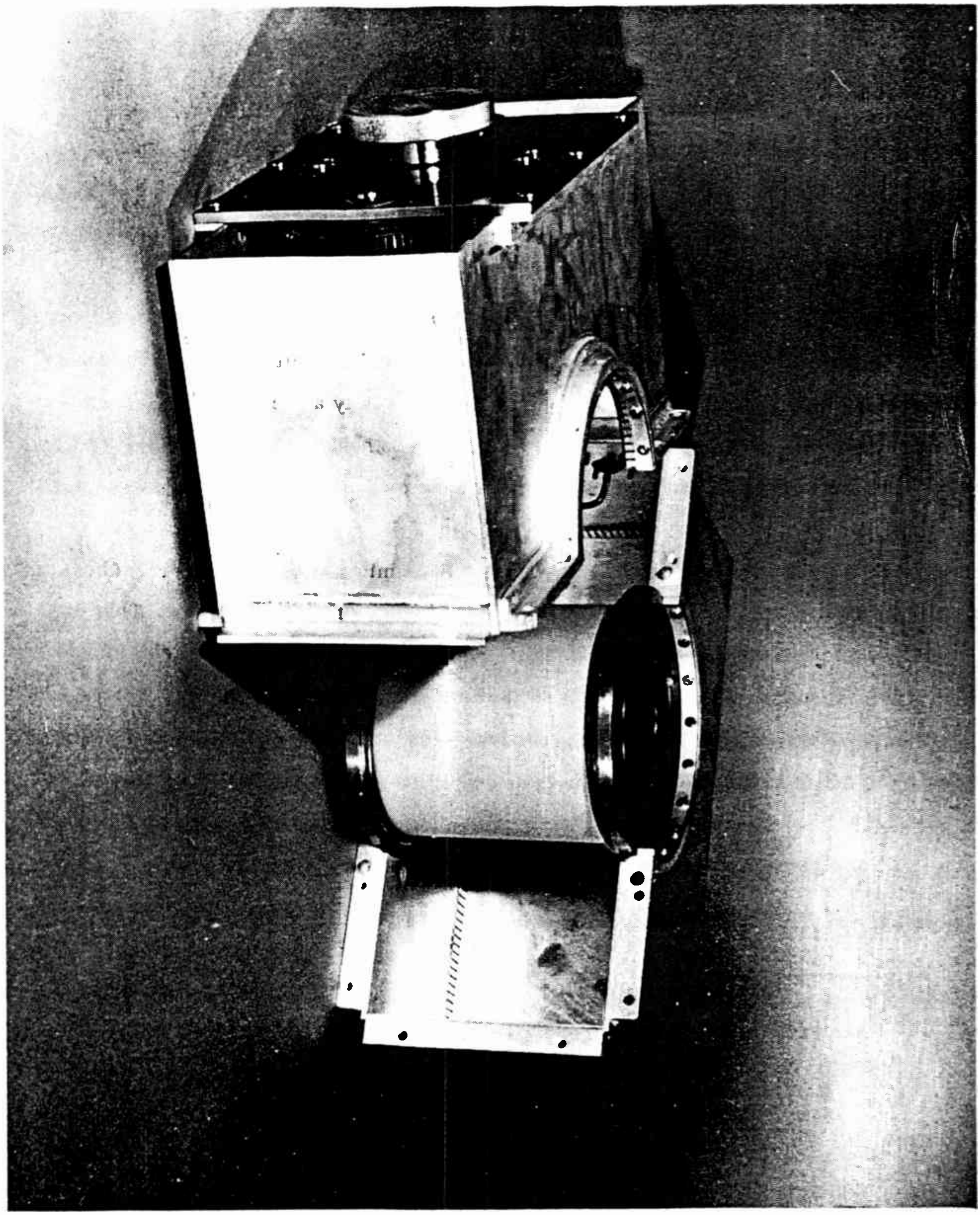


FIGURE 49: EXTERNAL CAVITY TUNING BOX AND TUBE CERAMIC SECTION
Photo courtesy of Varian Associates Inc.

In order to simplify some of the explanations in this section, comparisons will again be made with apparent equivalent low frequency circuits. However, there are some fundamental differences so the reader must be careful not to carry the analogies to the extent that he may lose sight of these differences.

Resonant circuits used with triodes and tetrodes at low frequencies (refer to Section 1.2) are generally composed of an inductance and capacitance (LC circuit), while the resonant circuit used with a klystron is invariably a metal enclosed chamber known as a cavity resonator (or re-entrant cavity). Do not confuse the klystron cavity with coaxial cavities that are used with conventional or special purpose triodes.

At first thought, one might conclude that such microwave circuits might be arrived at by extension of conventional transmission line and circuit ideas. This is often done by showing the resonant cavity of a klystron and a conventional coil and condensor as the same comparison (see Figure 50). The drift tube gap in the cavity is roughly the same as the capacitor in the low frequency circuit because alternating voltages at the rf frequency can be made to appear across the gap as previously mentioned.

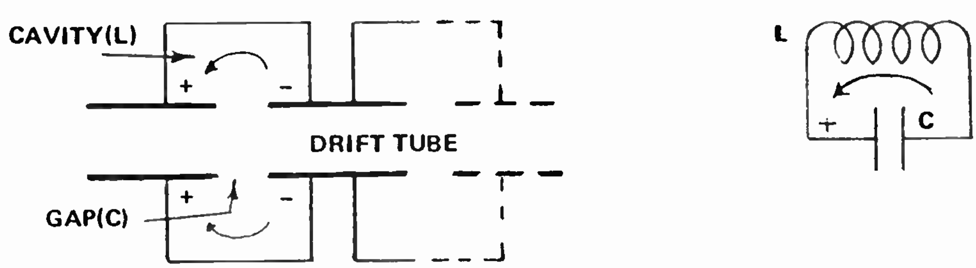


FIGURE 50 : RESONANT CAVITY AND EQUIVALENT CIRCUIT

This example is valid if we use it only as a simple comparison. There are other simplified analogies that are often used to show the evolution of klystron cavities. One of these may be familiar to our readers: the coaxial transmission line.

The coaxial transmission line is not generally thought of as being a cavity resonator at microwave frequencies, but it may very well be. If such a transmission line is shorted at both ends (see Figure 51), it is known that such a shorted line may support a standing-wave of a frequency such that the length of the line is exactly a half-wave. This coaxial line can be considered as resonant at that frequency, since the standing-wave pattern set up has constant total energy in the section of the line, oscillating between the electric and magnetic field.

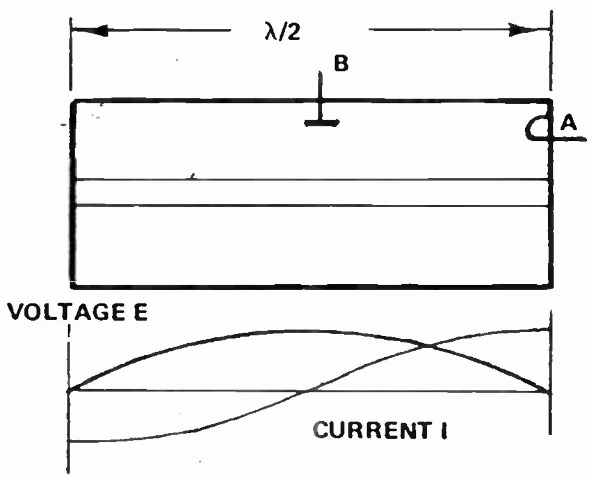


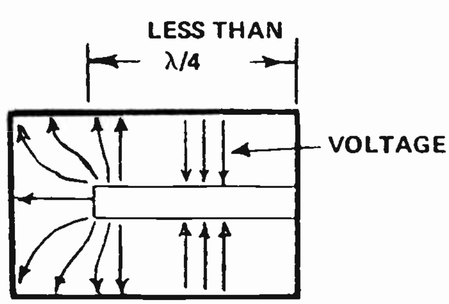
FIGURE 51: RESONANT COAXIAL SYSTEM AND STANDING WAVES OF VOLTAGE AND CURRENT

These standing-waves, as shown in Figure 51, will have zero voltage at each end of the line and maximum voltage in the center, the current standing-wave will be 90 degrees out of time phase with the voltage. Since this resonant line is completely shielded from the outside, it is necessary to excite the waves by some means. The probe shown at "A" will excite the magnetic field and the probe at "B" will excite the electric field. If one of these probes is used to excite the line with a constant signal at the exact resonant frequency, these oscillations may build up to a large value.

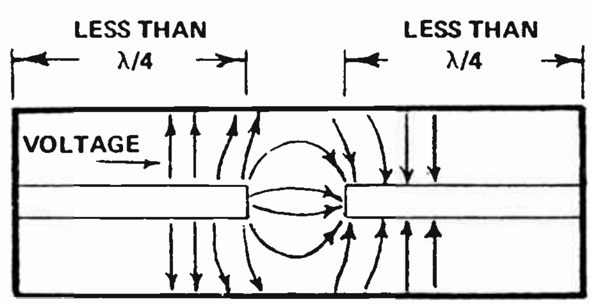
The amount of energy lost in the walls of the resonant line is small, while the relatively large stored energy is essentially constant and is oscillating back and forth between the electric and magnetic field.

If the resonant line is excited somewhat off of the resonant frequency by the signal source, the energies in the electric and magnetic fields do not balance. Some extra energy must be supplied over one part of the cycle which is given back to the source over another part of the rf cycle, and the line acts as a reactive load on the exciting source in addition to its small loss component.

Another example of coaxial line cavity employs a line section that is short circuited at one end and open at the other end of the center conductor, as indicated in Figure 52A. The outer conductor is closed around the open end of the center conductor so as to form a completely enclosed cavity. Because of the capacitance effect of the fringing electric field at the end of the center conductor, resonance occurs at frequencies for which the center conductor is somewhat less than an odd multiple of a quarter-wave. The frequency of the resonant line in Figure 52A is adjusted by changing the penetration of the center conductor into the cavity.



(A) QUARTER WAVE RESONATOR



(B) DOUBLE QUARTER WAVE RESONATOR

FIGURE 52 : RESONANT COAXIAL SYSTEMS OPERATED IN ODD MULTIPLES OF QUARTER-WAVE

If two of these quarter-wave resonators are placed together, it will appear as in Figure 52B. The electric field crosses each point in the center at right angles. Therefore, a thin conducting plane could be inserted at the position of this line without changing the field pattern. Each half of the resonator may then be considered as a coaxial line less than a quarter-wave, tuned to resonance by twice the capacitance between the ends of the center conductor.

The similarity of the coaxial transmission line in Figure 51 and 52 to a conventional LC circuit should be evident, yet they possess all the fundamental characteristics of a cavity resonator and differ only in the types of waves (modes) that are utilized. A mode is defined by the geometrical shape of the varying electric and magnetic fields within a given resonator.

A common practice in showing the development of a klystron cavity is to start with a single loop of wire or copper strap for the inductance and two disks as the plates of a condensor as shown in the illustration of Figure 53A. The resonant frequency of this simple circuit will be high, but in proportions shown will not be as high as the microwave frequencies. If the plates (capacitance) were moved apart, reducing the capacitance, the frequency would increase, but there is a practical limit to this approach. If the loop (inductance) were further decreased in size, the losses become excessive and the loop would, for all practical purposes, vanish before the true microwave region could be reached. However, the inductance can be reduced in another manner by adding other loops in parallel with the original one, eliminating stray inductance, until the two plates are connected by a solid conducting wall. We are now left with a completely enclosed volume with the strongest electric field across the center of the cavity (see Figure 53 B, C). As acceptable as this analogy may be in the development or creation of a cavity resonator, one should not take it literally, as the true capacitance and inductance are not as definite as the illustration assumes. Although it would appear safe to conclude that the condensor plates have actually been shorted so that if any voltage can exist between them, it can only exist at the center and must form a standing-wave pattern in the cavity, falling to zero at the walls and so requiring it to have a diameter at least comparable to wavelength. It may also be assumed that the side walls have been imagined to act as an inductance.

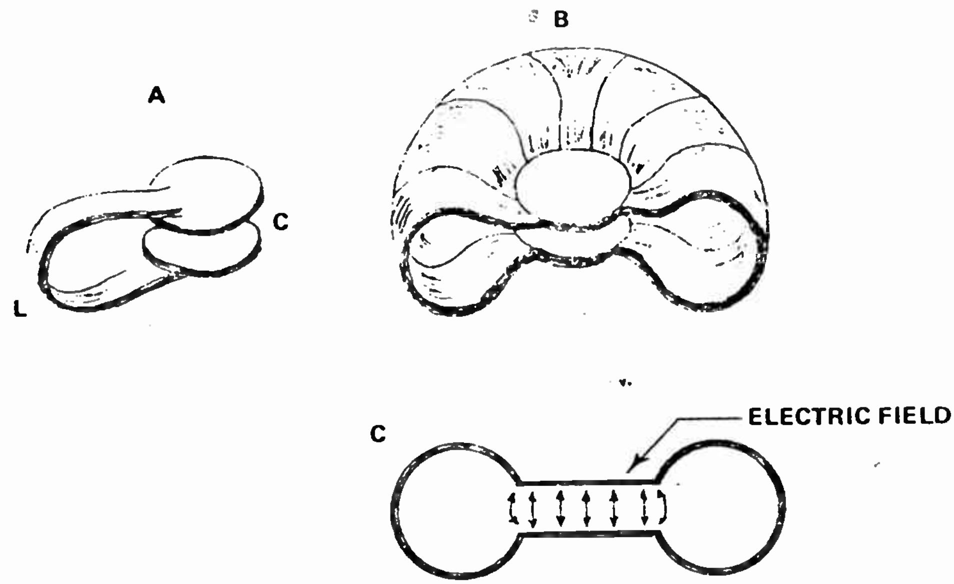


FIGURE 53: FORMATION OF REENTRANT CAVITY

It should be remembered that for any circuit to be resonant, the inductive and capacitive reactance of each component must be equal and this is true for resonant cavities. Individual reactance of the components in the equivalent circuit of Figure 50 can be found by conventional means since each component can be measured separately. However, the individual components within the cavity of Figure 53 are next to impossible to distinguish from each other as they cannot be measured as separate units. Capacitance effects occur between various parts of the inductance loop as well as between the plates; thus such effects are important enough that they must be recognized in design calculations. Not being concerned with cavity design calculations in this text, and aside from using inductance and capacitance relating only to the phase of the electric and magnetic field, they're of little use at this time. A simpler way to visualize the capacitance and inductance of a klystron cavity without compromising basic theory is as follows:

1. The capacitance of a cavity is concentrated where the voltage is maximum, and this occurs across the gap formed by the entrance and exit drift tubes.
2. The inductance of a cavity is concentrated where the voltage is at a minimum, and this occurs within the outer volume of the cavity.

By defining the L and C components of a cavity in the above terms, it becomes very easy to visualize changes in the volume as changes in the inductance and changes effecting the gaps as changes in the capacitance.

The resonant cavity illustrated in Figure 53 may be familiar to some readers, this is the "rumbatron cavity" first conceived by W.W. Hansen [5] and later refined by Russel H. Varian and Sigurd F. Varian[6] with the invention of the klystron, which was the earliest form of re-entrant cavity. This cavity must also be excited similar to the resonant coaxial line of Figure 51, by either a probe or loop into the cavity at some convenient location. Although the first klystron built was an oscillator, shown in Figure 54, the first essential of a klystron amplifier or oscillator is the creation of a <u>bunched beam</u> which carries an rf component of current*(bunching will be discussed in detail later in this section). How was this accomplished with the cavity illustrated in Figure 53B and C? First, the two capacitive disks which became the narrow dimensions of the cavity were made with holes or wires to form grids. This then allowed a beam of electrons to pass through the cavity at the highest voltage point. The grids form short circuits as far as the oscillations are concerned. Electrically, then, this cavity resembles a length of coaxial line, shorted at each end with a break in the inner conductor where the grids are located. Across the break (gap), a large rf voltage is developed when the cavity is excited. It is this voltage which accelerates or slows down the electrons

---

5 "A High Frequency Resonator," By W.W. Hansen, Journal of Applied Physics, Volume 9, October 1938.

6 "A High Frequency Oscillator or Amplifier," By Russel H. Varian and Sigurd F. Varian, Journal of Applied Physics, Volume 10, May 1939.

* This is a generally accepted explanation; however, a detailed analogy of bunching is covered in Section 5.3.

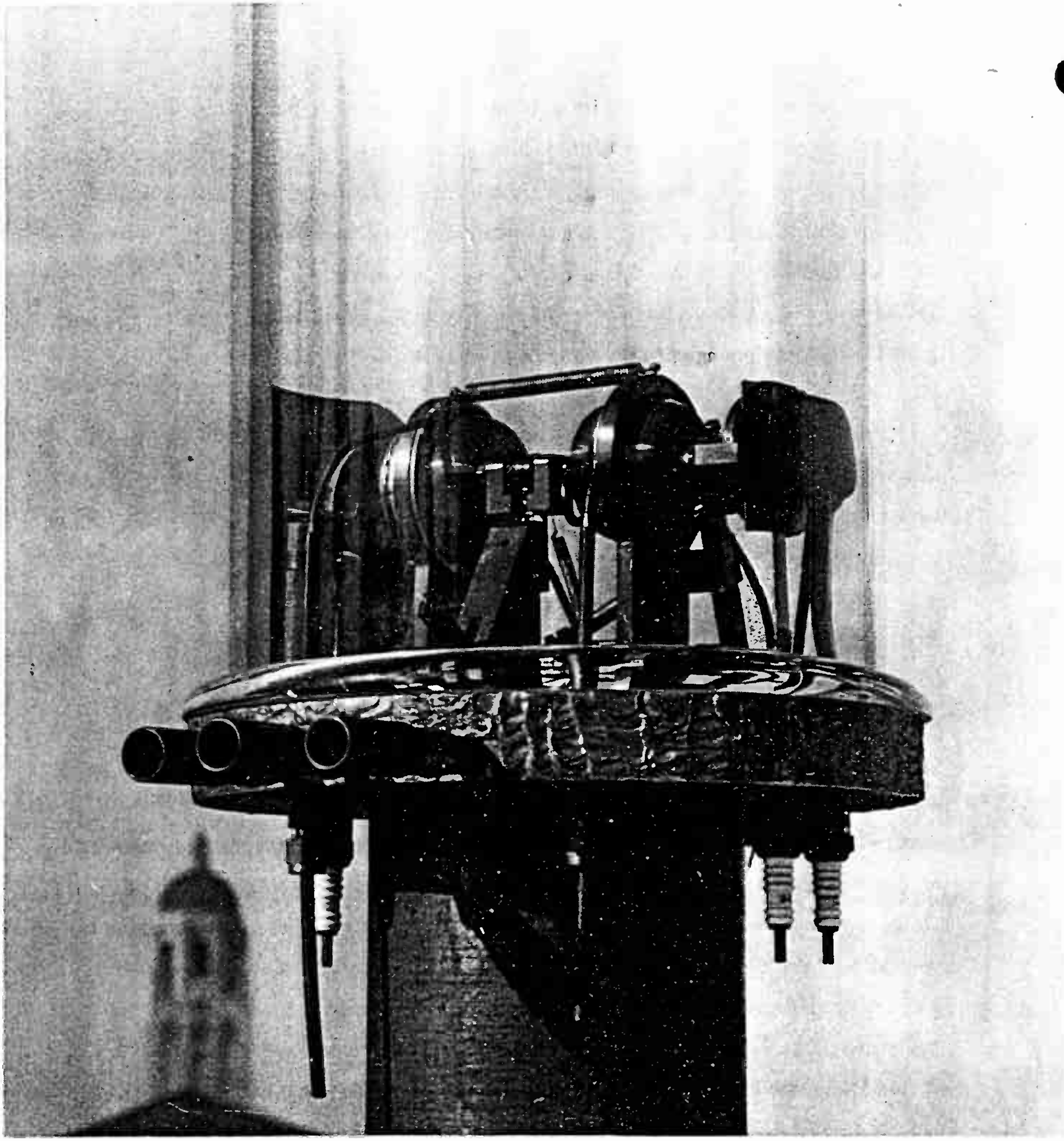


FIGURE 54: FIRST KLYSTRON OSCILLATOR, BUILT BY VARIAN BROTHERS
Photo courtesy of Varian Associates Inc.

passing through the cavity. The electrons must pass through the electric field between these two capacitive disks formed into grids in a time that is less than one-half cycle. Generally speaking, a much shorter transit time would be desirable. This would make it possible to have a greater variation of current in the resonator. For example, if,in an extreme case,the transit time across the gap is a whole cycle as a function of the rf frequency, the coupling would fail altogether because the average current in the cavity would remain constant. How close the grids (or drift tube ends) can be brought together to reduce the transit time, is ordinarily limited only by voltage breakdown and secondary emission problems.

Early klystrons did use grids across the drift tubes in the cavities as do many present-day reflex klystrons and some low power klystron amplifiers. However, on higher power tubes, they would be destroyed by the beam as previously mentioned.

This analogy of cavities was only pointed out to show part of the evolution of klystron cavities. You are by no means restricted to the rumbatron shape for re-entrant cavities. Other forms of re-entrant cavities are shown in Figure 55, and you will note that they have considerable resemblance to the quarter-wave resonator previously shown in Figure 52. Re-entrant cavities in these forms may be thought of as being a result of employing the quarter-wave resonator principle at such high frequencies and with such narrow spacings between the center conductor end walls that the line length becomes comparable to or less than the transverse dimensions.

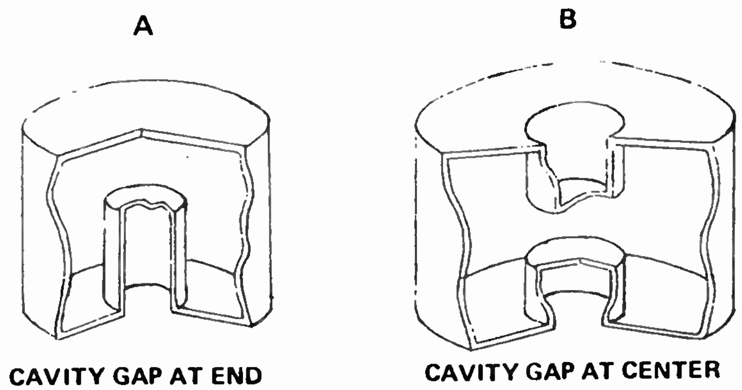


FIGURE 55: REENTRANT CAVITY FORMS

5.2 Cavity Tuning

The resonant frequency of a klystron cavity may be changed by one of three basic methods, and they are:

1. Changing the inductance by moving a wall of the cavity to change the volume of the cavity.
2. Changing the capacitance of the drift tube gap by insertion of a probe in the vicinity of the gap.
3. Changing the capacitance of the drift tube gap by changing the spacing between the drift tubes.

Figure 56 illustrates the technique of moving one of the walls of a resonant cavity to increase or decrease the inductance for tuning. Internal cavity klystrons use a thin metal diaphragm that is part of the vacuum seal and attached to a suitable tuning mechanism in order to change the resonant frequency. External cavity klystrons use an external door or sliding wall to tune the cavity. Either of these methods accomplish the same result.

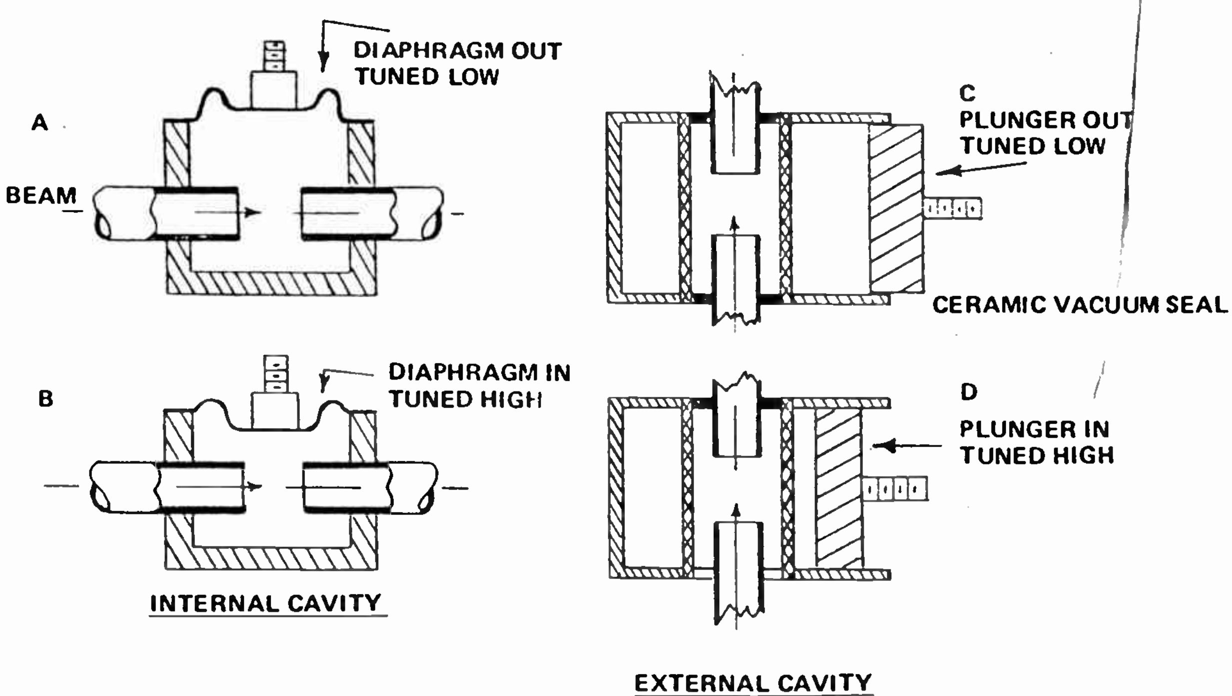


FIGURE 56: INTERNAL AND EXTERNAL CAVITY INDUCTIVE TUNING

Figure 56A and C illustrate a diaphragm and a sliding wall pulled out so the inductance is increased and the resonant frequency is decreased. In Figure 56B and D, the diaphragm and sliding wall are pushed in,decreasing the inductance and increasing the resonant frequency. External cavity klystrons for UHF-TV use the method of a sliding wall for tuning,while the diaphragm method is generally used on physically smaller klystrons, used for radar or communications, where the cavities are small enough to make it practical to use a thin metal diaphragm as part of the cavity wall.

Figure 57 illustrates the second method of tuning by changing the capacitance. A probe can be attached to a thin wall diaphragm (or bellows), so the end of the probe is close to the drift tube gap. What little change in inductance there is with the bellows, has little or no effect on the frequency. The main control is the probe or paddle that is in the vicinity of the drift tubes.

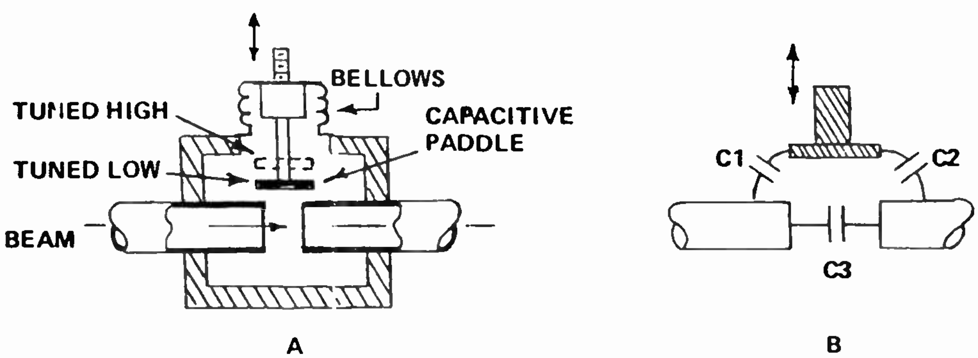


FIGURE 57: CAPACITIVE TUNING METHOD

Figure 57A represents the tuning configuration and Figure 57B represents the gap area of the cavity and how capacitance are formed between the paddle end of the probe and the drift tubes at the gap. By moving the metal paddle close to the drift tubes, capacitors C1 and C2 are formed across the capacity of the drift tube gap labeled C3. As the paddle is moved closer to the gap, the values of C1 and C2 are increased. Because C1 and C2 are across the capacitance of the cavity gap (C3), the total capacitance of the combination is increased. By increasing the capacity, the resonant frequency is decreased. Moving the paddle away would decrease the total capacitance at the gap and cause the resonant frequency to increase. Internal cavity klystrons for UHF-TV use this method of tuning cavities and are generally in the form of a bellows rather than a thin diaphragm.

The third method of tuning a resonant cavity is illustrated in Figure 58. Here, again, the capacitance of the gap is changed by making one of the cavity walls next to the drift tube thin like a diaphragm, allowing the drift tube to be moved in and out of the cavity.

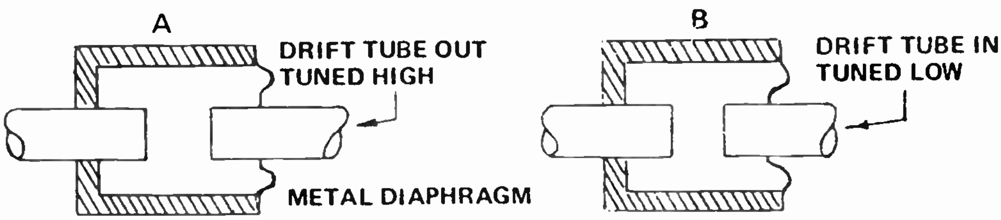


FIGURE 58: CAPACITIVE TUNING WITH MOVABLE DRIFT TUBE

When the movable drift tube is pushed in (A), increasing the capacitance, the frequency is lowered. When the drift tube is pulled out (B), decreasing the capacitance, the frequency is increased. This type of tuning is not generally used with multi-cavity klystrons because the length of the cavity must change in order to tune the cavity. In 4 or 5 cavity klystrons (large or small physically), the overall length change can add up to a considerable amount, and the alignment of the drift tubes would be difficult. The above method has been used on some experimental laboratory klystrons and is still used for tuning many types of reflex klystrons.

Of the three basic methods, typically, internal cavity klystrons for UHF-TV use a capacitive paddle and a bellows for tuning and the external cavity klystron for UHF-TV use an inductive sliding door (or wall) on one or both sides of the cavity box for tuning (see Figure 49 and 59).

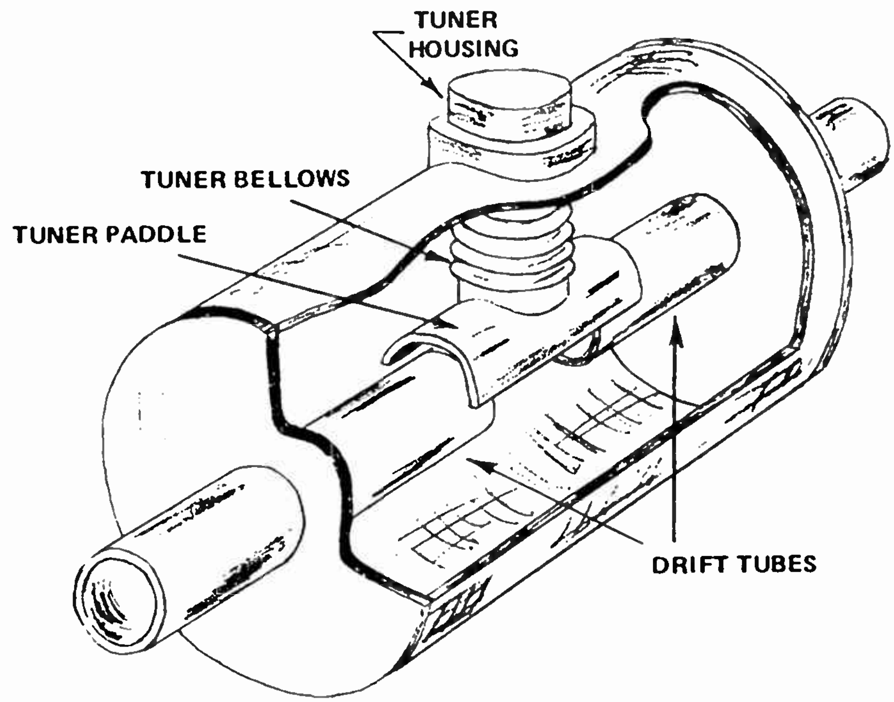


FIGURE 59: CUT-AWAY VIEW OF TYPICAL INTERNAL CAVITY FOR UHF TV KLYSTRONS

5.3 Bunching Principles

Having covered the basic concepts of the klystron cavity, let us now consider how it works when used as part of a klystron amplifier.

Many publications relating to electron bunching in klystrons often show the election beam as a rippling beam (or boloney sausage if you prefer) to illustrate the bunching effect. It is true that there is scalloping of the beam at various positions along the drift tube lengths due to certain circumstances, but not to the extent as often portrayed in most illustrations. Obviously this approach has been used considerably, however it is not a good concept to adhere to in visualizing the overall bunching phenomenon. The boloney sausage analogy is more adaptable and correct for waveguide theory and operation in illustrating group and phase velocity of the rf wave and should not be confused with the bunching of an electron beam. In this text the electron beam will be portrayed as a linear beam. The scalloping of the beam will be explained later in the text.

When electrons are emitted from the hot cathode, they are confined by the magnetic field that is around the klystron, into a continuous stream of electrons in their passage through the drift tubes. This beam of electrons can be simply compared to a direct current of electricity confined to a wire. Obviously the electron beam in a klystron is not confined to a wire, never the less it is a direct current of electricity flowing through the free space of the drift tubes.

In addition, just as direct current produces no sound as it travels through earphones, so a direct current electron beam produces no rf power as it travels through a klystron. It must be modulated in some manner before it can be usefull, and in the klystron this is accomplished at the drift tube gaps by supplying rf power to the input cavity resonator which in turn causes an interaction between the rf source and the electrons in the beam. The applied rf power develops an oscillating voltage at a rate equal to the rf frequency, across the sides of the cavity gap. This alternating voltage will cause the alternate sides of the input gap to become first positive and then negative, causing some electrons to be slowed down and accelerating others as they pass through the drift tube gap. The result is that in a time period of one cycle of the rf wave beyond the point where the electron velocity is varied or perturbed, there will appear a greater density of electrons or greater density of current.

This greater density of electrons can be illustrated simply by assuming one could view the electrons passing by a point down stream in a time period of one cycle of the rf (see Figure 60). For example in Figure 60A there are 13 evenly spaced rows of electrons (or 52 total) passing in a time period of one cycle of the rf. There is no rf power assumed in this case but I have used the time span of one rf cycle for counting electrons. In this example there is some average current associated with these uniformly spaced electrons, this is continuous and represents the average beam current of the tube. In other words, in Figure 60A each row of electrons is 1/13 of the one rf cycle, and since the electrons have the same velocity, 4 electrons pass every 1/13 of the rf cycle.

In Figure 60B, some value of rf drive power has been applied to the input cavity and now as the electrons pass the same point down stream in a time period of one cycle of the rf, we still have 52 electrons but they are spaced differently due to their velocities

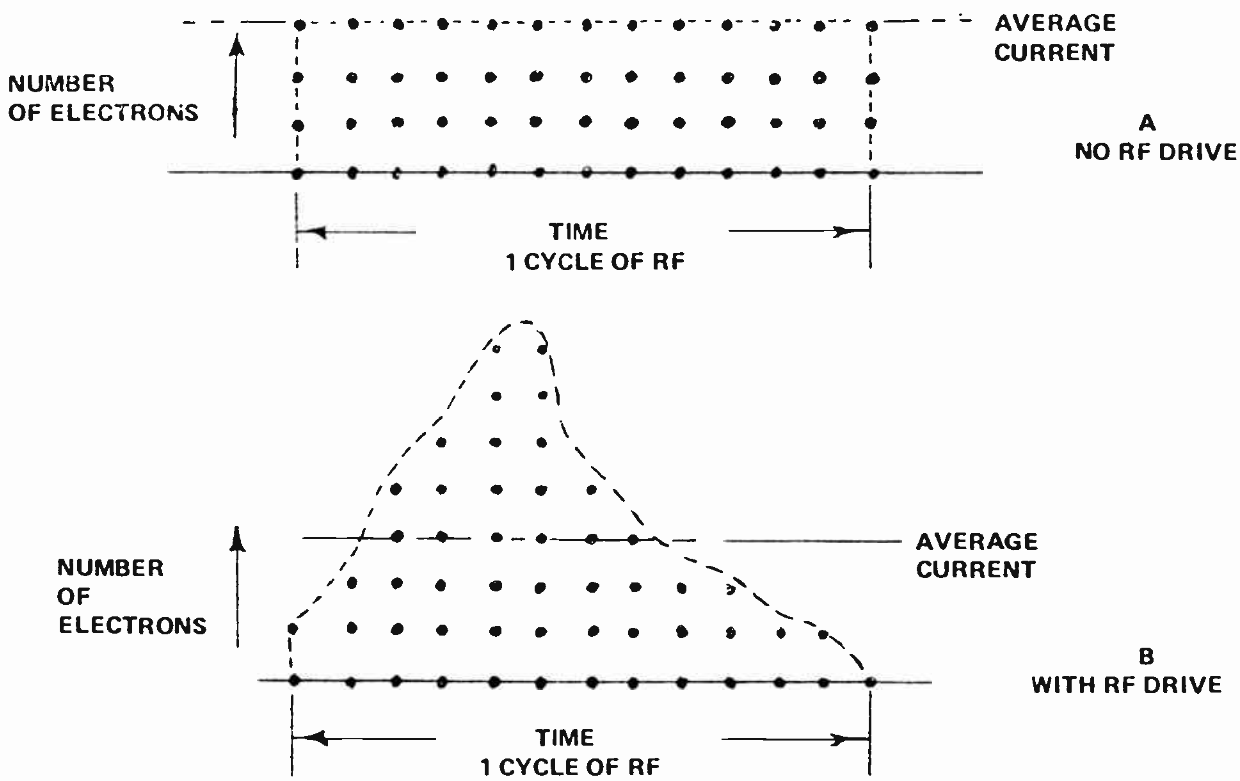


FIGURE 60: CURRENT RESULTING FROM PASSAGE OF ELECTRONS BETWEEN RESONATOR GAP

being perturbed. The current associated with these groupings give rise to a pulse of current due to the density difference across the total time period. It is interesting to note that the average of this current pulse is still the same as the steady state value shown in Figure 60A. The beam current really hasent changed, the same amount of electrons has passed the same point in space.

The electrons in Figure 60B may progress through 3, 4 or more cycles of the rf time period before reaching the next cavity where the electrons have formed into an appreciable bunch and a resultant current build up. For every time period of the rf wave the electrons progress, the density or pulse will be different due to the velocity difference of the electrons. However, in all cases the total quantity (52 in this example) will be the same. It is the current pulse that reacts with the next cavity giving rise to amplified rf power. This in essence is what is called the bunching principle due to velocity modulation. It is generally acceptable to say that after these electrons pass through the input cavity they will form into tighter bunches as they travel through each subsequent cavity gap and will induce an alternating current to flow in each cavity, and when they arrive at the output cavity they will have formed into what is called optimum bunching. In view of this, it is frequently said that the velocity modulation imparted to the beam when it passed through the input gap, gives rise to current modulation farther along the beam.

The intermediate cavities between the input and output cavity are coupled only by the electron beam at the gaps when rf power is applied to the input cavity, changing the velocity of the electrons. There are no external sources of rf coupling or power to the intermediate cavities.

Quite often new students involved with klystrons confuse the +DC connection to the body and the external DC return path of the collector and body to the power supply as having something to do with the rf coupling between cavities. It is only a return path for the DC electrons to the power supply and has nothing to do with rf coupling between cavities. The electron source in a klystron is completly independent of the rf circuit. The rf field created at the input cavity controls the bunching, and the currents associated with the fields will flow in a thin layer on the interior conducting surfaces of the resonator, —— no rf current will flow on the outside of the cavity. There is one qualification to the above statement regarding, "no external rf connections to the intermediate cavities." Some klystrons, due to design, do have rf fittings attached to intermediate cavities for external loading to increase the bandwidth response of a particular cavity. A typical example is pictured in Figure 61, indicating the location of the external load connections for one of the intermediate cavities. However, most of the present day UHF-TV klystrons have adaquate loading for bandwidth due to different design parameters, thus eliminating the external rf fitting.

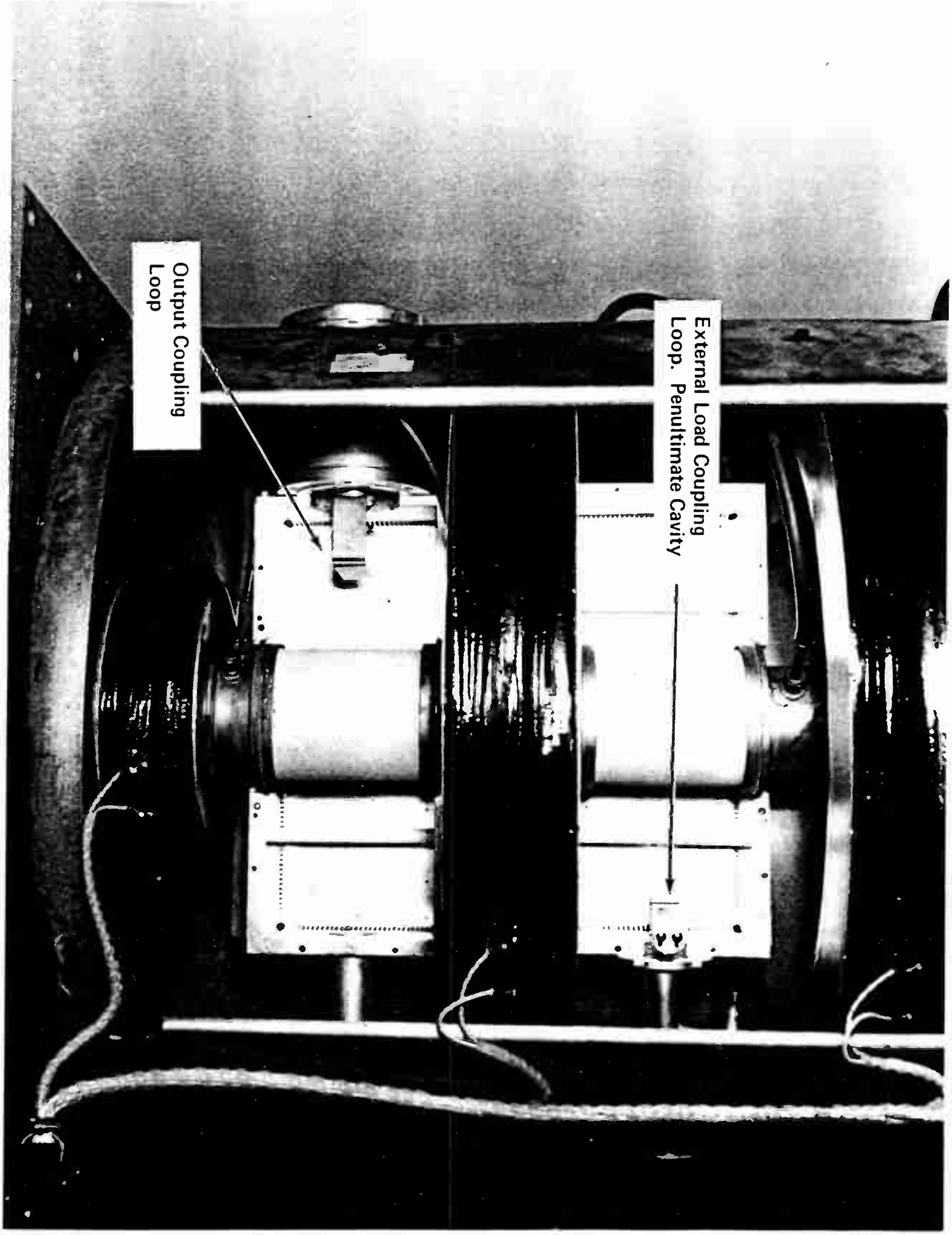


FIGURE 61: EXTERNAL CAVITY KLYSTRON SHOWING EXTERNAL LOAD COUPLING OF INTERMEDIATE CAVITY AND OUTPUT COUPLING LOOP
Photo courtesy of Varian Associates Inc.

5.4 Interaction Between an Electron Beam and a Resonant Cavity

The velocity modulation created at the input gap is not difficult to understand; the electron is a negatively charged particle and it can be accelerated or decelerated by the electric field at the input gap which was created by applying rf power to the cavity. It has also been established that a current pulse is created when the electrons tend to bunch. However, the transfer of energy from what is called the bunched beam (or current pulse) to the intermediate cavities or to the output cavity is not so obvious and is often avoided in discussions by mearly assuming that there is a constant alternating field present at each of these cavities and that the electron beam gives up some of its kinetic energy to maintain this field.

A bunched electron beam will build up the field in a cavity in the same way an alternating current (rf) flowing in a resonant LC circuit will build up a voltage across the circuit. This can be explained very simply; first it should be obvious that the beam density is uniform and is direct current at the position of the input cavity, but with the change in velocity of the electrons there will be a pulse of current at the next cavity gap when the electrons form into what is called a bunch (or current pulse). Second, while this current pulse is in the drift tube gap there will be a field induced in the gap since a field always accompanies an electron charge, and this induced field will alternate from positive to negative across the gap.

NOTE: Some authors prefer to use the phrase; the bunched beam carries an rf component of current or an alternating component of current is superimposed on the direct current beam when the electrons pass through the input cavity.

Obviously this has been an acceptable explanation, however it may tend to be misleading as to how rf is generated in each intermediate or output cavity. This should be evident as you progress in the text.

The current pulse (or electron bunch) arrives at the next gap in the right time phase so that the field induced in the cavity reacts upon the moving electrons, slowing some down and accelerating others and further strengthening the original bunch. The energy given up by the electrons in the current pulse due to the slowing down process remains in the resonant cavity as a residual field, and the build up process has started.

In effect, the passage of an electron or group of electrons between the drift tube gap causes a positive charge, equal in magnitude to the electron charge, to move from the entrance drift tube to the exit drift tube and back again. Other current pulses (electron bunches) will of course pass through the cavities in a time rate equal to the rf frequency, in turn inducing an alternating field to build up in the resonant cavity. For each cavity the electron bunch passes through, the current will build up until they reach the output cavity where the bunch is most well formed.

The exchange of energy in the output cavity is the same as the other intermediate cavities, except the energy given up by the electrons to the output cavity is coupled to the outside through the transmission line to a dummy load or antenna. The remaining energy in the beam is dissapated in the collector in the form of heat when the electrons strike the inside surface.

It should be evident now why a uniform stream of electrons (uniform density) does not create rf even though a field always accompanies an electron charge. There must be some initial change in velociy of the electrons to create a greater density of the electrons at some point and less dense at another point within a time period of one cycle of the rf wave. The density of these electrons of course gives rise to a current pulse which is predicated upon the amount of rf applied at the input cavity and of course the beam voltage.

It can also be said that the rf drive power that is applied to the input cavity does not travel to each subsequent cavity to be amplified, as is the general impression, it travels no further than the input cavity. RF is generated in the intermediate cavities by the fact that the uniform beam of electrons was converted to a bunched beam or pulsating current. The field accompanying this current pulse (electron bunch) thus can induce a field into each cavity at an rf rate. Power is delivered to the output cavity load because at resonance the phase of the oscillation in the output cavity is such that the maximum decelerating voltage appears across the output cavity drift tubes when the maximum number of electrons is crossing the gap. This follows from the fact that at resonance the cavity and load appear as a resistance connected between the drift tubes, so that when the induced current reaches maximum, the voltage across the cavity gap is also maximum. This then explains the transfer of energy from the beam to the cavity.

Figure 62 pictures one variety of output cavity design used with an internal cavity UHF-TV klystron, showing the output coupling, tuner and one of the drift tubes. The external cavity tube section and tuning box shown in Figure 61 is equivalent in many respects to that of Figure 62 other than physical shape.

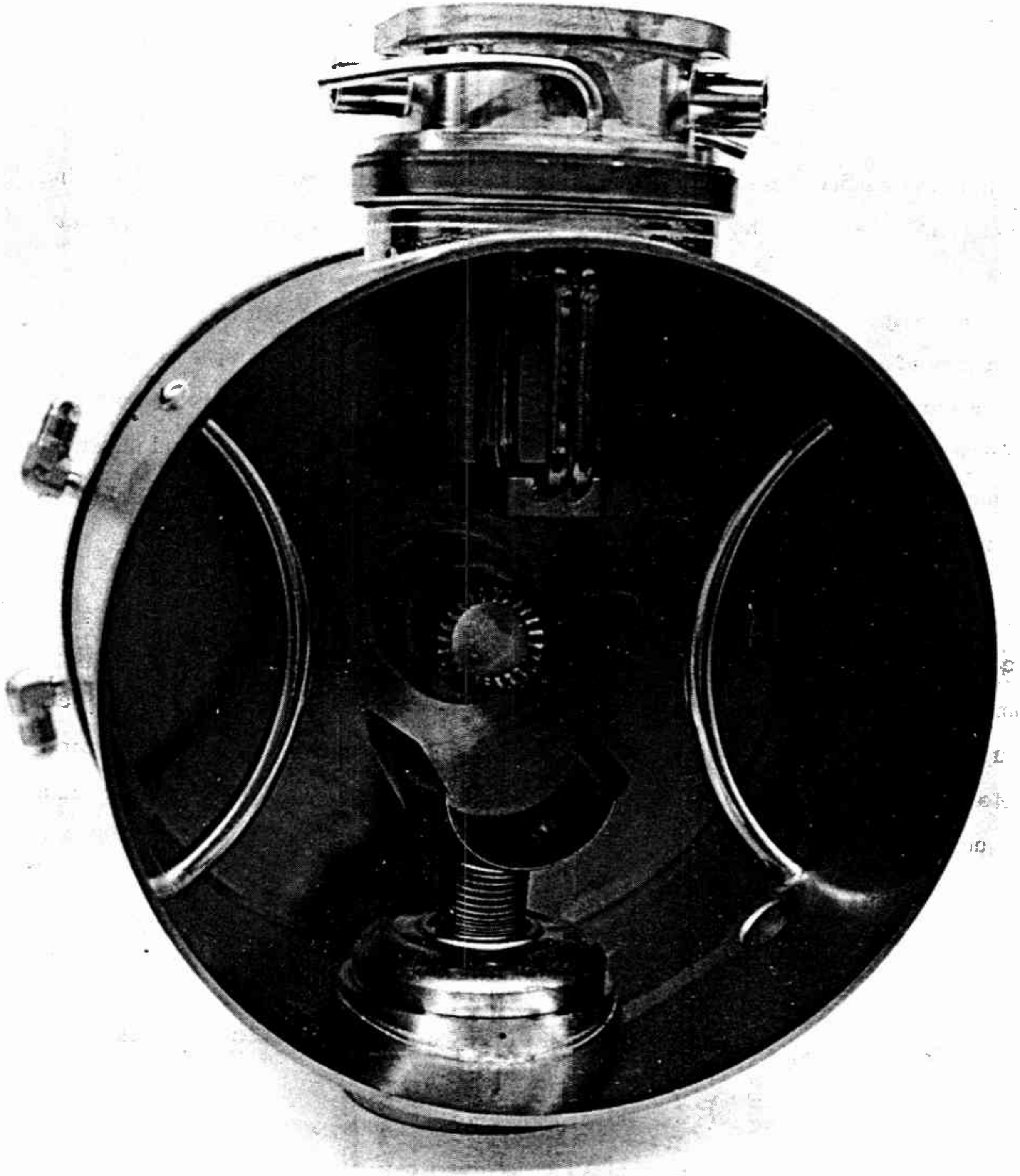


FIGURE 62: OUTPUT CAVITY OF INTERNAL CAVITY KLYSTRON SHOWING OUTPUT COUPLING LOOP AND TUNING PADDLE
Photo courtesy of Varian Associates Inc.

5.5 Bunching Action

In order to complete the overall picture of the bunching principles, let us now examine the mechanism in more detail by which the velocity modulation and bunching occurs in the region of the drift tubes by various pictorial and graphical representations.

Initially, it will be assumed in this part of the discussion that the resonant frequency of all cavities from the input to the output are the same as the rf drive power source. When all cavities operate on the same frequency, this is commonly referred to as synchronous operation, which results in the highest gain and minimum bandwidth. This is important to remember as the different methods of tuning will be covered later.

As discussed earlier, all of the initial acceleration of the electrons occurs at the electron gun before they enter the input cavity area. These electrons approach the input cavity with equal velocity and are not yet formed into bunches. When rf power is applied to the input cavity, an oscillating electromagnetic field is developed completely within the cavity, if the cavity is the right size (eg; that is, tuned to the right frequency), see Figure 63.

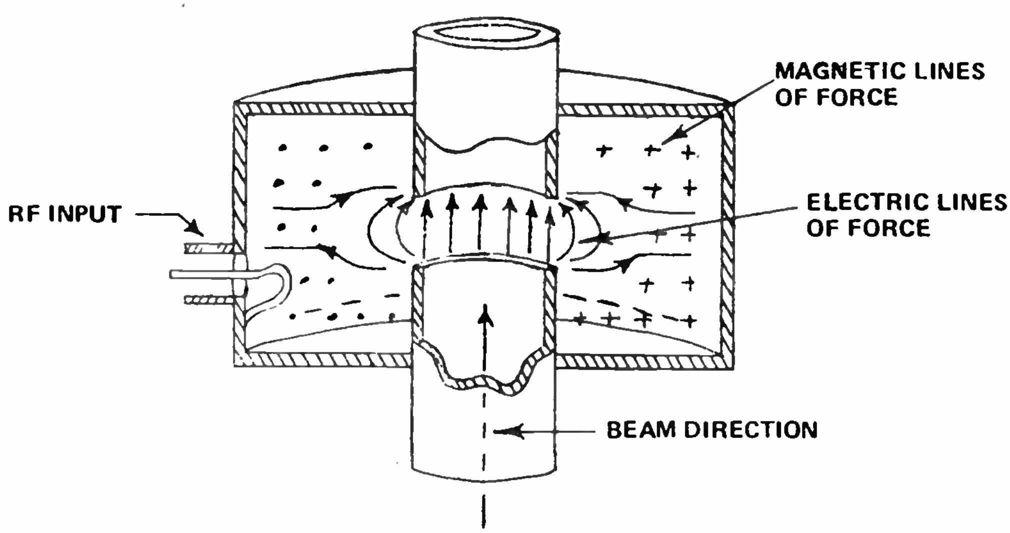


FIGURE 63: ELECTRIC AND MAGNETIC LINES OF FORCE IN A KLYSTRON CAVITY

This oscillating current will cause the alternate sides of the input cavity gap to become first positive and then negative in potential at a frequency rate equal to the frequency of the rf input signal. This electric field will for half a cycle, be in a direction which will tend to speed up the electrons flowing through the gap. On the other half of the cycle the electric field will be in the direction which will tend to slow down the electrons as they cross the input cavity gap.

Remember the earlier discussion on electrons, a negative potential will repel and a positive potential will attract the electrons. The result is of course that the electrons are acted on by the changing potential on the drift tubes and they will form into bunches (or current pulses as previously explained). This change in voltage at the drift tubes can be simply illustrated as an oscillating voltage as shown in Figure 64.

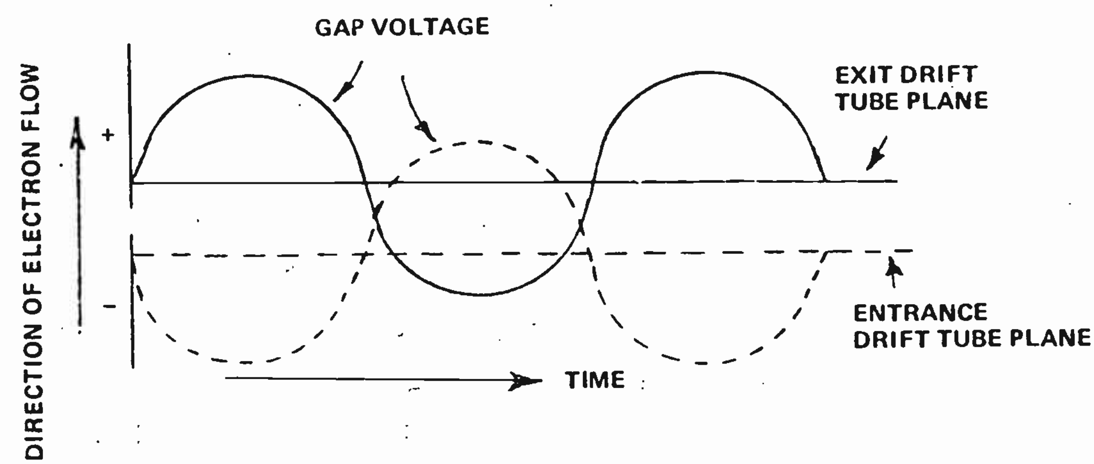


FIGURE 64: DRIFT TUBE GAP VOLTAGE ASSOCIATED WITH ELECTRON FLOW

Now let us apply this concept of the alternating voltage at the drift tube gap and assume that we can view the input cavity at four instants in time as the electrons flow past the gap in some time period. (See Figure 65)

NOTE: For this illustration I have shown the electrons arriving at the input cavity as bunches only for visual clarity of the progression through the cavity.

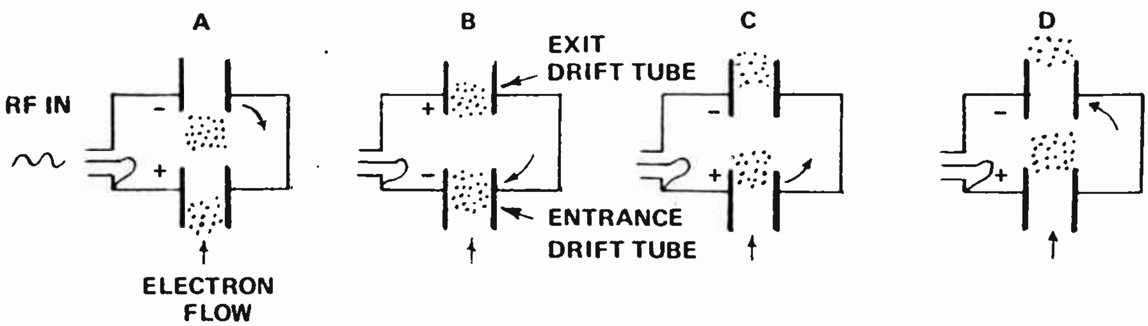


FIGURE 65: SIMPLIFIED BUNCHING ACTION DUE TO ELECTRIC FIELD POLARITY ON DRIFT TUBES

Figure 65A shows the input cavity, which has had rf power applied. The negative electrons approaching the exit drift tube area of the cavity have been accelerated by the charge on the entrance drift tube an in turn causing an electron current to flow away from the exit drift tube area of the cavity. In Figure 65B, the electrons are now in the exit drift tube and the current in the cavity is continuing to flow away from the exit drift tube, thus leaving the exit drift tube positive. Average electrons following will be speeded up because of the positive charge now. In Figure 65C, the electrons following are still in the input drift tube and the cavity gap voltage is starting to swing back to the negative exit drift tube condition. Electrons which are within the gap at this time are slowed down and will fall back into the electrons now starting to enter the gap.

> NOTE: The electrons don't actually fall or move backwards. They have just been slowed down enough that some will become part of the electrons behind them which will be speeded up.

Figure 65D then shows these electrons entering the gap and this completes the cycle. This process of course repeats every cycle of the rf wave because there is a continuous stream of electrons flowing past the input cavity gap.

The electron bunching illustrated above in Figure 65 is an overly simplified presentation, however the interpretation does no harm as the important part is the basic understanding of the acceleration and deceleration period of the electrons. As mentioned earlier, the electrons enter the input cavity gap in a continuous stream and the bunching created by the voltage at the drift tube gap actually takes place after the exit drift tube in the field free space of the drift tube as previously described at the beginning of section 5.3.

Consider now a more concice presentation of the time, distance and the gap voltage envolvement upon the electrons passing through the input cavity. The bunching process can be illustrated in another manner with the aid of a graph called an Applegate Diagram,[7] which is sometimes used in design calculation (see Figure 66). In this diagram, or graph if you prefer, the time of the electron traveling is measured along the horizontal axis and the position (distance from the exit drift tube face) of the electron along the drift space is plotted in the verticle axis.

The rf voltage shown below the graph is relative to each electron at the input gap at any instant of time, thus each verticle slanted line represents the space-time history and velocity of a particular electron in the beam. It is also interesting to note in the resulting set of lines that the density of the slanted lines along any horizontal line corresponds to the magnitude of the current as a function of time as was illustrated previously in Figure 60. It should also be pointed out though, that the applegate analysis neglets space-charge effects in the electron beam and assumes that the transit time between the resonator drift tubes is negligable. Space-charge effects very simply is debunching of the beam caused by the mutual repulsion of the electrons as they are bunched tighter. Space charge effects will be covered in more detail at the end of this chapter.

[7] "Graphical Methods For Analysis of Velocity Modulation Bunching," By A. E. Harrison, Proc IRE, January 1945.

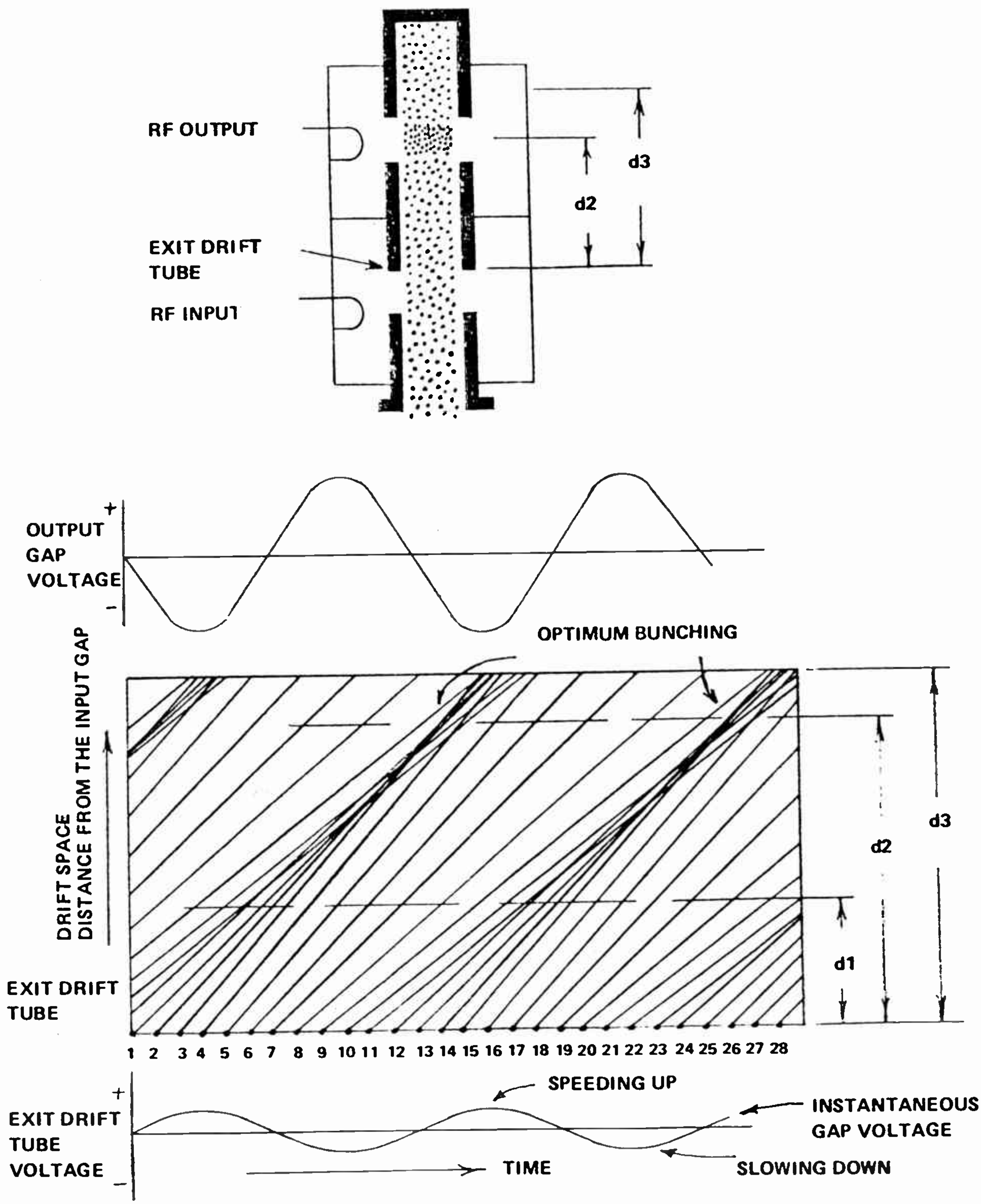


FIGURE 66: BUNCHING PROCESS IN A CAVITY RESONATOR BY VELOCITY MODULATION, NOMINAL DRIVE LEVEL

Contrary to the impression of many, the maximum or optimum bunching in multi-cavity klystrons does not occure in each intermediate cavity (there is appreciable bunching but not maximum). The maximum or optimum bunching, which is the most preferable term, occurs at the output cavity. So in this part of the bunching explanation it will be more instructive in showing the variations of the electrons by ignoring the intermediate cavities for the moment and use only a two cavity amplifier example. Once this basic concept is covered, the second part will show the effect on the intermediate cavities. In both cases though, optimum bunching still occurs at the output cavity. I have also choosen for this explanation, three drive levels called low drive, nominal drive and high drive, also distance d2 as the position of the output gap for optimum bunching.

The electrons are represented by the numbered dots (1, 2, 3 etc) in Figure 66 at the instant they pass the exit drift tube of the input cavity and the verticle lines are plots of the distance each electron has penetrated into the drift space. Thus the slope of the lines are proportional to the velocities of the electrons (which is dependent on the rf drive voltage and beam voltage). In examining the plot of Figure 66, the steep line for electron number 4 (or 16) may be correlated with the gap voltage for maximum acceleration and electron number 10 (or 22) for the maximum decelerating gap voltage or lower velocity electron. The convergence of the lines around the center electron number 1 at distance d2 indicates optimum bunching. This is also illustrated in the two cavity amplifier above the graph along with a relative output voltage for a nominal rf drive power.

You will note that just before the line indicating distance d2 that there is just formed a tight bunch that is very narrow and has a high current associated with it. This is the convergence point of the electrons around the center electron. A little further down the beam the bunch gets a little wider and it is this point that has the highest current associated with the edges. This is the optimum bunching point and when it occurs at distance d2 this is what is called saturated power output.

The convergence of the electrons around the center electron number 13 at distance d2 will be in a time period of one cycle of the rf wave later, to make the second bunch (or current pulse). Of course other bunches follow behind, repeating the process. Distance d1 indicates an appreciable bunching but in actually building a tube you would want the output gap at the point where the greatest density of electrons occur, and in this example, this will be at distance d2 is illustrated in Figure 66.

If we could stop the action of the electrons as illustrated in the Applegate Diagram of Figure 66, we could see the distribution of the electrons as the beam moved along the drift space. Let us assume we could view the bunching action at eight different time periods as they progress toward the output gap. In Figure 67, a line is drawn through a center reference electron which would be similar to electron number 1(or 13) of Figure 66. If you follow the reference electron, starting at the input gap, then move to the second or third column, the bunch becomes more compact. As the bunch continues to move along the drift space, the bunch becomes slightly wider but more electrons become part of this wider bunch as they cross the output gap.

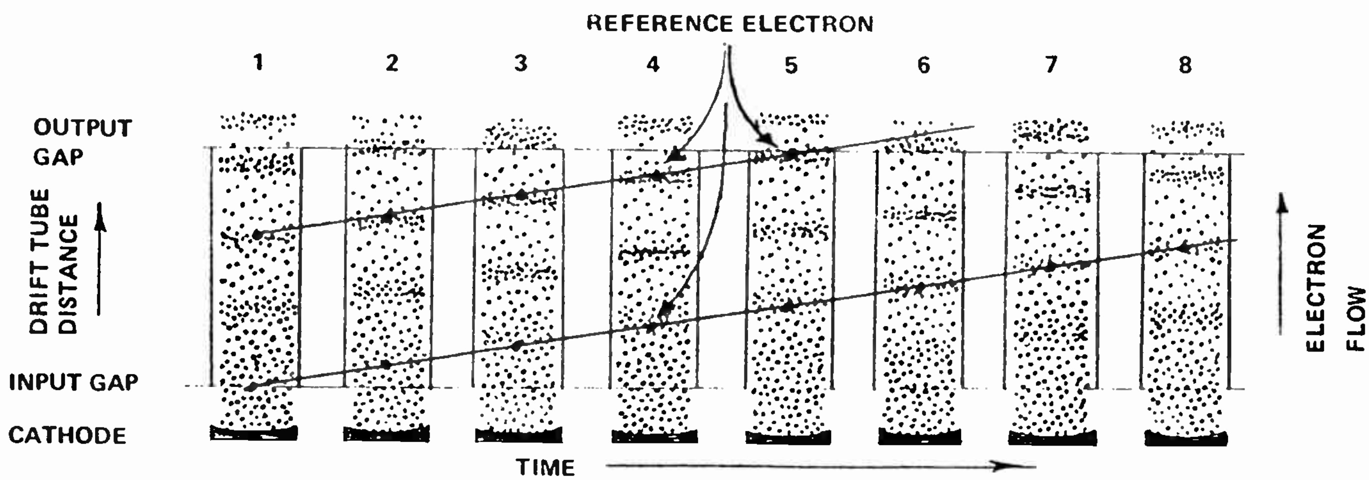


FIGURE 67: ELECTRON DISTRIBUTION AND BUNCHING IN KLYSTRON DRIFT TUBE AT EIGHT DIFFERENT TIME PERIODS

In carrying the applegate examples a little further, if the rf drive power was made smaller, the rf drive voltage will also be smaller and the slopes of the electron trajectories will be smaller (eg; slanting more to the right) indicating less accelerating and decelerating force on the electrons and the distance out to the optimum bunching would be greater (see Figure 68). In other words, if you had a fixed drift tube length (distance d2), there would be some bunching at d2 but not optimum and the power output would be lower than indicated previously in Figure 66. You would need a drift tube greater than the length indicated by distance d3 for optimum bunching. This is an underdriven condition where the tube is operating in the small signal region.

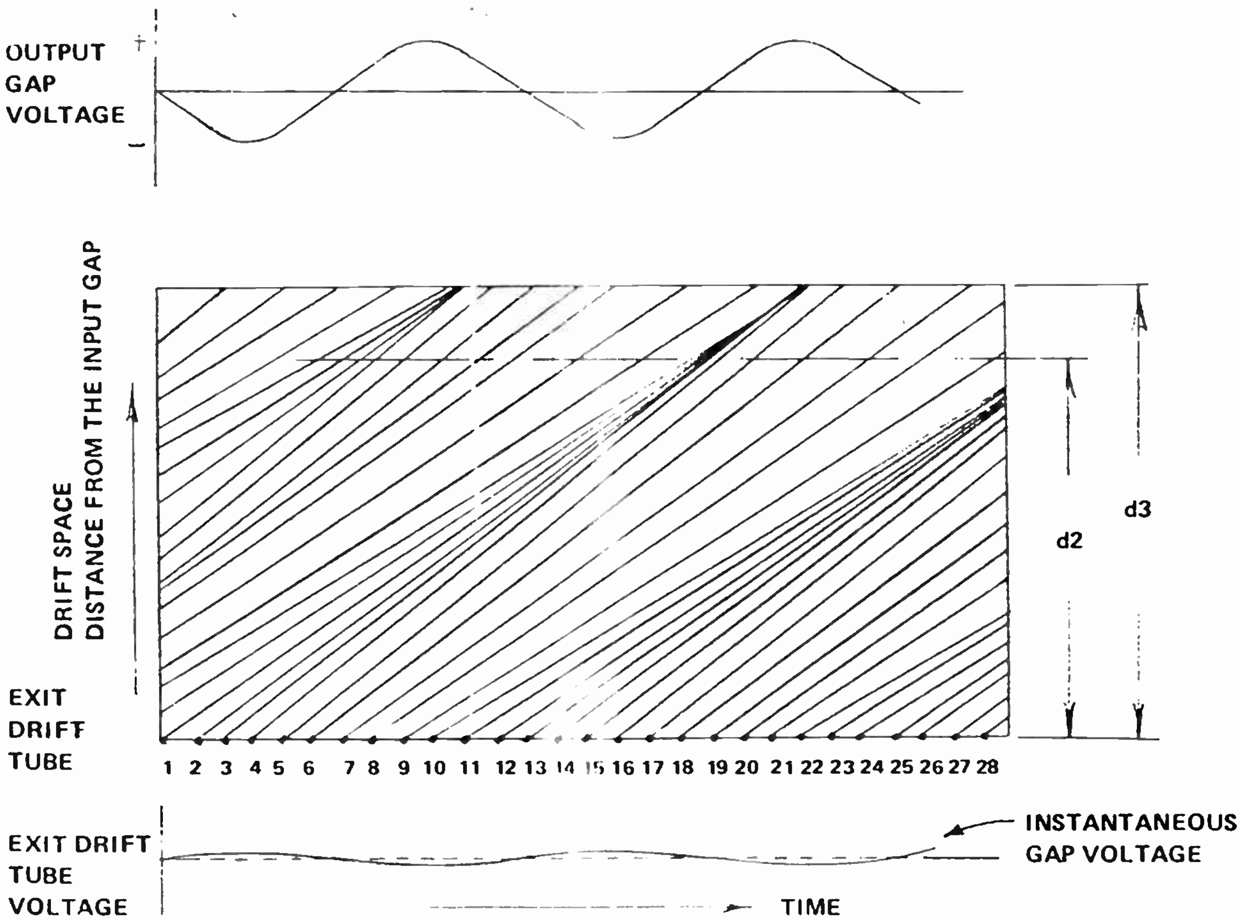


FIGURE 68: BUNCHING PROCESS IN A CAVITY RESONATOR BY VELOCITY MODULATION, LOW DRIVE LEVEL

Conversly, if the rf drive power is higher than normal, the rf voltage will be larger an there will be overbunching of the electrons. In this condition, the slopes of the trajectories will be larger and the bunching occurs earlier at distance d1 (see Figure 69). The power output of the klystron will also decrease because the bunches have formed too soon and will arrive at the output gap in what is an overbunched condition.

NOTE: For the record, the general defination for overbunching is; the condition which exists in a velocity modulation tube when the drift tube is too long, or what amounts to the same thing, if the input gap voltage and/or the accelerating beam voltage are too high.

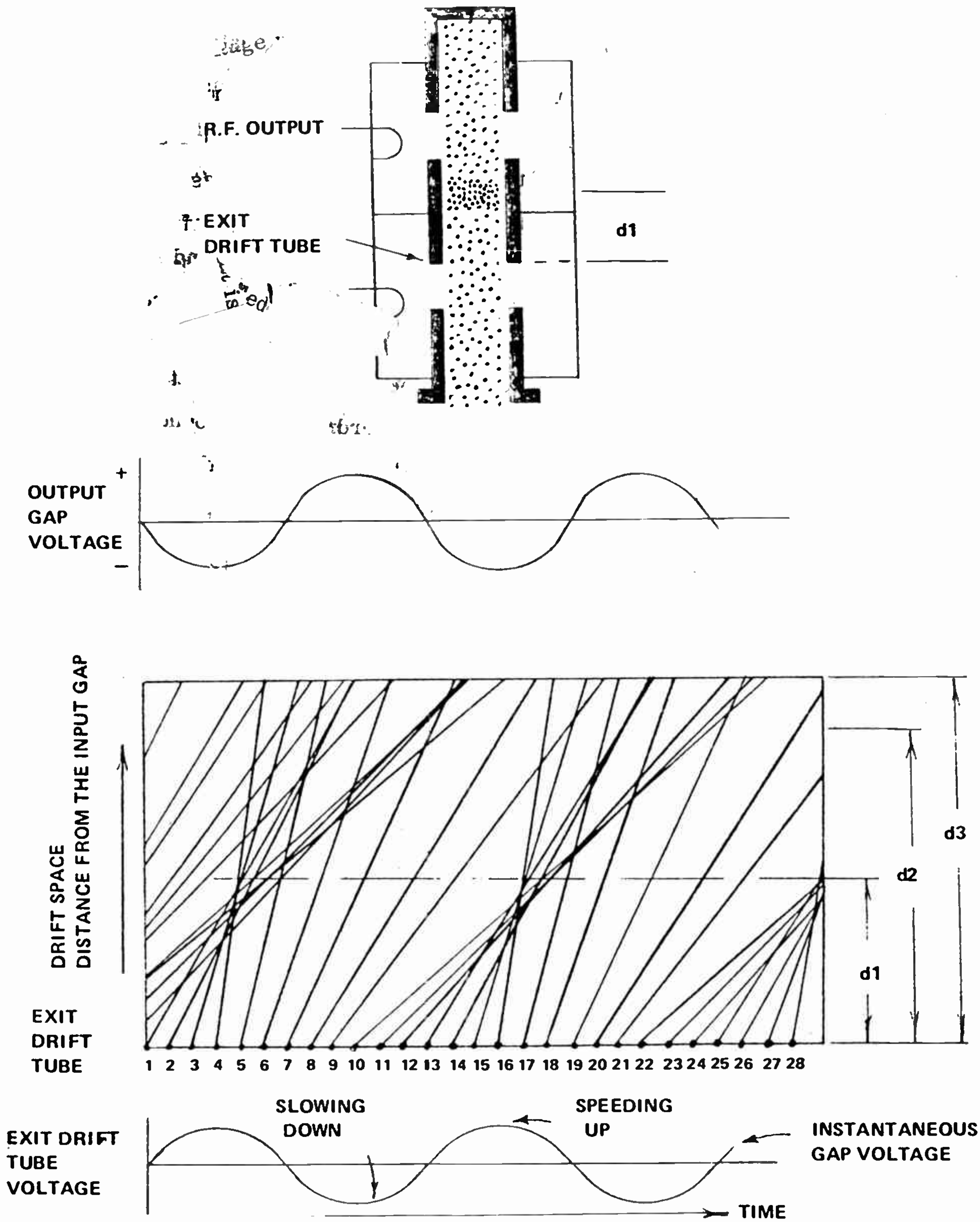


FIGURE 69 : BUNCHING PROCESS IN A CAVITY RESONATOR BY VELOCITY MODULATION, HIGH DRIVE LEVEL

It should be obvious from Figures 66 and 69, that a klystron will saturate just as a triode will limit. It is possible under conditions of high rf drive as shown in Figure 69, that by the time the electrons reach the output cavity, the faster electrons will have caught up with the slower ones which were originally ahead of them and may actually pass the slower ones. If this extreme condition existed, a second bunching may start to form when the slower electrons are overtaken and a second power output peak may be produced (but lower than the main peak). Figure 69 does not show a complete second bunching but if you examine it closly you can see the tendency for the formation of a second bunch near the output cavity at distance d2. Figure 70 illustrates this condition when the tube is overdriven.

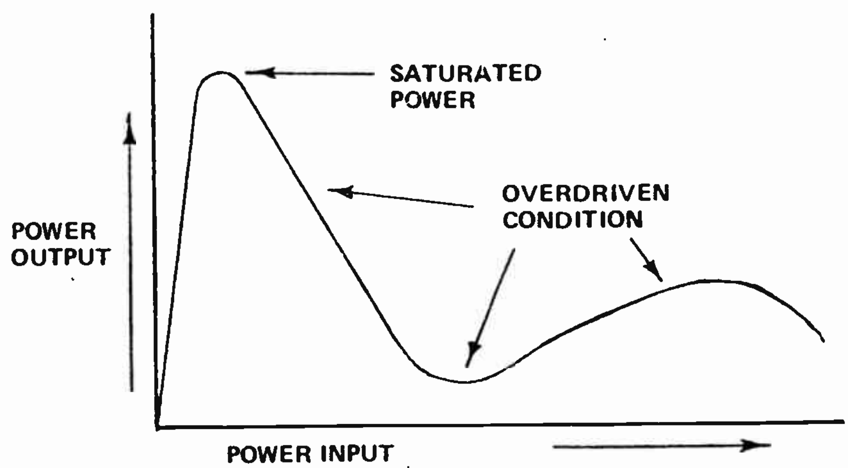


FIGURE 70: POWER INPUT vs POWER OUTPUT

The graph of Figure 70 is called a transfer curve. It is a typical theoretical curve of Power Output (output cavity) as a function of rf Power Input to the first cavity and is representative of any klystron amplifier, whether it is a 2 or 5 cavity tube. The peak of the curve labeled Saturated Power is the maximum power that would be achieved if the rf drive were adjusted to the conditions as shown in Figure 66 for nominal drive. The area labeled on the curve as Overdriven and 2nd Power Peak is what would happen if the conditions of Figure 69 for high rf drive were applied to the input cavity of a klystron. As the rf drive is increased from zero, the bunching reaches optimum at the output cavity where saturated power is indicated, and by further increasing the rf drive the output power will drop.

The tube is now in an overbunched condition as in Figure 69. A further increase in rf drive and the overbunching may develope a second bunch, indicated by the sec d power peak. If you have stumbled into this condition and have not yet damaged or des oyed the tube (eg; a burnt tuner or drift tube), it would be well advised to reduce the rf drive power to the proper level.

Since the examples of bunching so far have been of two cavity amplifiers, overdriving (causing overbunching), generally is not disastrous if this is the type of tube yo re dealing with because most all operate at relatively low power. Although, as a rule, you should not overdrive any klystron, and this is especially important to remember when dealing with multi-cavity klystrons (see section on overbunching).

5.5.1 Bunching Action in Multi-Cavity Klystrons.

The bunching and interaction principles covered in sections 5.3, 5.4 and 5.5 utilized a two cavity klystron as an example for simplicity of explanation, also it was assumed in all cases that all cavities were tuned to the same frequency, indicating the tube was synchronously tuned. With the understanding of these basic principles, the bunching action in a multi-cavity klystron will now be easier to follow.

The bunching and interaction of the electrons in a multi-cavity klystron is still the same except a little more complex. With additional cavities, complexity arises from the fact that the voltage at each cavity influences the current not just at the cavity immediatly following, but at all of the following cavities. Adding more cavities to a klystron is roughly analogus to adding more stages to an IF Amplifier; eg, the gain of the overall amplifier is increased and the overall bandwidth is reduced, that is, if all of the stages are tuned to the same frequency. This same effect also occurs with the klystron, however, by broadband tuning, the bandwidth can be increased in both cases.

There are many applications where certain types of klystrons are operated in the synchronously tuned condition or close to it. However, additional power and bandwidth are often required, such as with UHF-TV or communication type klystron applications. This may be relized as stated above by stagger-tuning various cavities, trading gain for bandwidth.

NOTE: The term stagger or broadband tuning are synonymous with each other and are often interchanged when making reference to the tuning method.

Specifically the factors and relationships that effect the increased bandwidth are perveance, efficiency, power and the cavity shunt resistance to Q ratio. The output cavity must also have a bandwidth at least equal to the desired bandwidth of the complete klystron.

All cavities in a multi-cavity klystron except the output cavity can be considered as a driver section, and clearly in designing a driver section for a broadband klystron, a great many variables are available to the designer. In addition to the relationships mentioned above, this incledes the number of cavities, the electron transit time through the gaps of the individual cavities (which effects the electron beam loading of the cavities) and the drift distance between the individual cavities.

Actually, all of these areas mentioned above are important in the design of any klystron, whether it is to be a broadband operated tube or not. Another technique in maximizing the bandwidth is by designing the individual cavities in the driver section so they have minimum capacitance and maximum inductance. Sometimes it is necessary or desirable to flatten the frequency response of an individual cavity in the driver section by lowering the Q. The Q of a cavity can be lowered by artificial external loading or by designing the cavity with a longer gap between the drift tubes, as mentioned above, so as to increase the effective loading by the beam. Figure 71 pictures a klystron used for UHF-TV with an external load connected to the penultimate cavity (next to last cavity). This cavity loading is similar to the external cavity klystron shown earlier in Figure 61, but as mentioned before, most of the presently designed klystrons for UHF-TV, no longer require external cavity loading.

NOTE: With 4 or 5 cavity klystrons, the additional cavities will of course improve the slight bunching after it continues past the second gap, also there will be complete bunching by the time the electrons reach the output cavity.

The gain in a velocity modulated multi-cavity klystron is relatively independent of the input rf voltage when the voltage is small, and the gain is greater than the gain of an amplifier with sufficient bunching to give optimum output (see Figure 72).

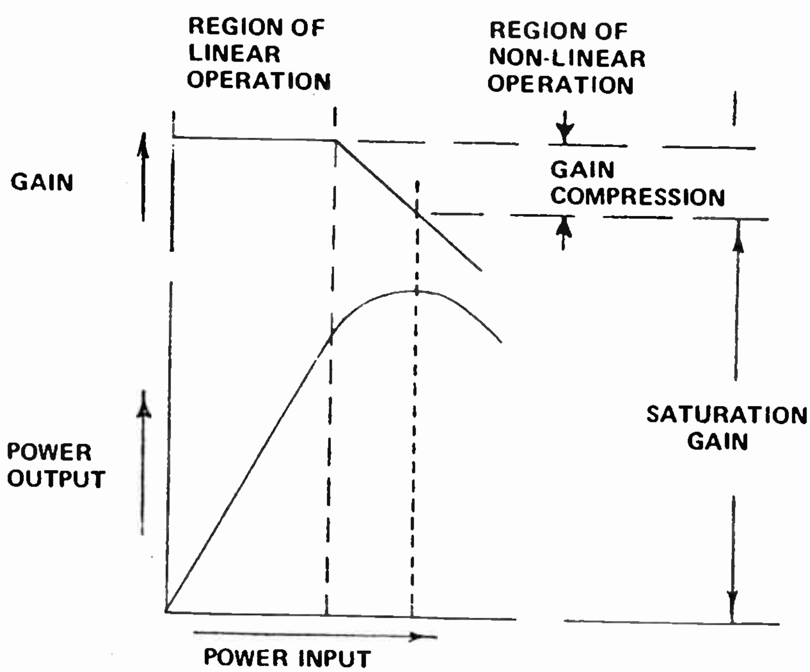


FIGURE 72: GAIN VS POWER OUTPUT

The graph of Figure 72 is another transfer curve of rf Power Output (output cavity) as a function of rf Input Power to the input cavity. It is the same as Figure 70 except for the labeled areas of concern.

In Figure 72 you can see the gain is essentially constant over the linear region of operation and exhibits a decrease in gain (or gain compression) as peak power or saturation occurs. This condition is also true for klystrons tuned for broadband operation. In addition, the gain of the first stage or input cavity, is sufficient to introduce a much larger voltage at the second gap, and this will of course increase with additional intermediate cavities. This means that a large velocity variation is imposed on the partly bunched beam at the second cavity gap even with a small amount of rf driving voltage at the input cavity. This velocity variation is much greater than that introduced by the input cavity gap owing to the voltage gain in the input cavity, and this additional variation may give sufficient bunching for optimum output at the third cavity (output cavity) as illustrated in the Applegate diagram of Figure 73.

Before examining the plot of Figure 73, I must qualify my choice of cavity reference voltages. Since the average drift tube transit time determines in part the phase of the voltage at each cavity, I have choosen a 90 degree shift as an average for this example of synchronous operation, as were the Applegate examples of Figures 66, 68 and 69. The actual phase change of the voltage from one cavity to another in a specific tube is not criticle to this explanation and was only choosen for simplicity. Although it should be understood that even with a qualitive approach such as this, the results still not only will depend on the relative amplitudes of the velocity modulation but will be determined by the phase angle between the voltages in the different cavities and the phase relation between the cavity voltage and the bunched beam. The amplitudes of the voltages are purely arbitrary but are representative of a typical amplifier.

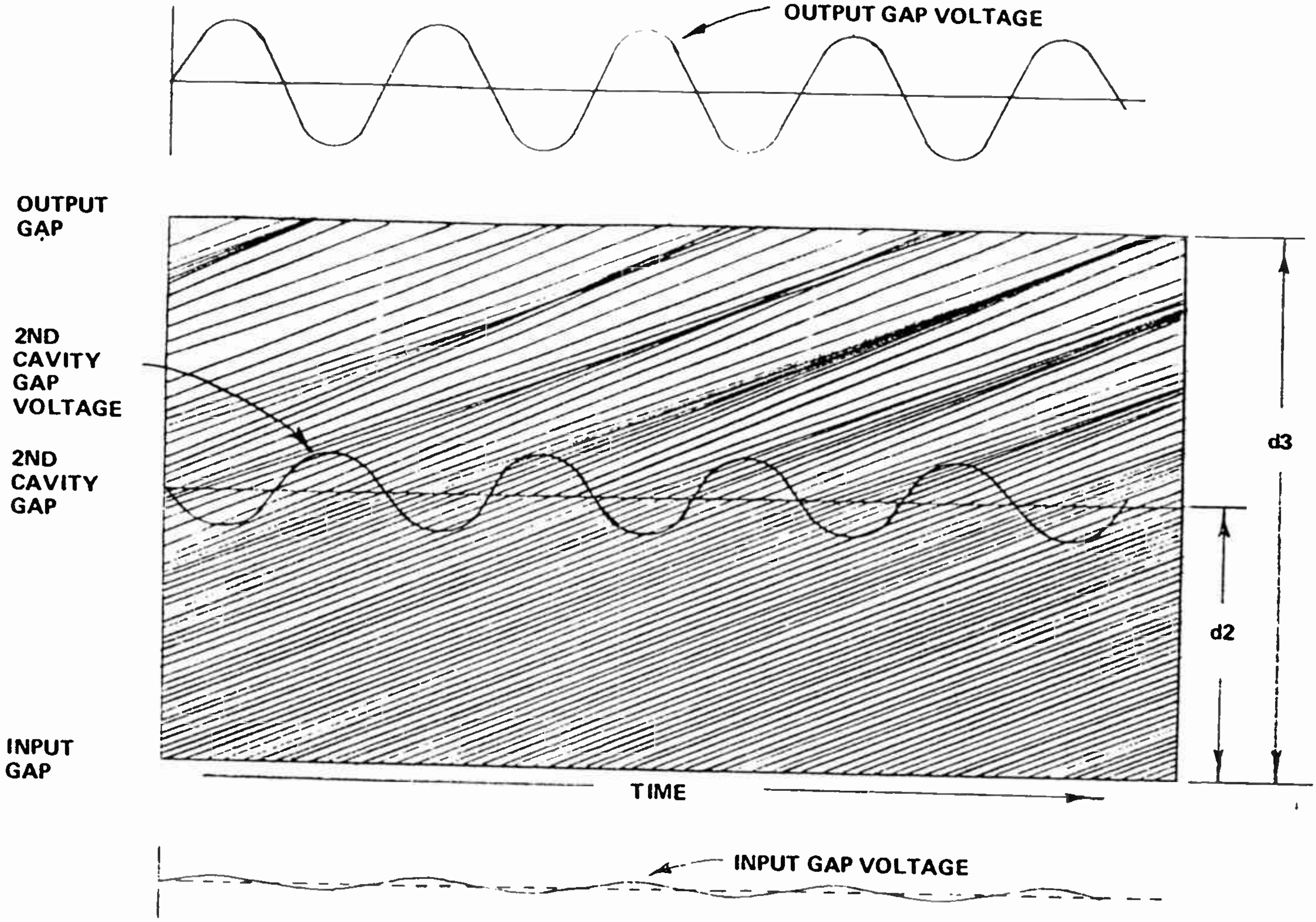


FIGURE 73: BUNCHING PROCESS IN MULTI-CAVITY KLYSTRON WITH ALL CAVITIES TUNED TO INPUT FREQUENCY (SYNCHRONOUSLY TUNED)

Distance d2 was again choosen to represent the position of the second cavity and distance d3 the position of the third or output cavity.

The Applegate example of Figure 73 represents a three cavity klystron synchronously tuned. You will note that there is phase difference of 90 degrees between the initial rf voltage at the input cavity and the bunching voltage at the second cavity if the second cavity is tuned to the same frequency.

NOTE: In addition, there is another 90 degree voltage shift in the output cavity as illustrated. This effect will also be true if all resonant circuits in a 4 or 5 cavity klystron are tuned to the same frequency. Figure 74 is representative of the Applegate diagram of Figure 73 in showing the bandpass of each cavity.

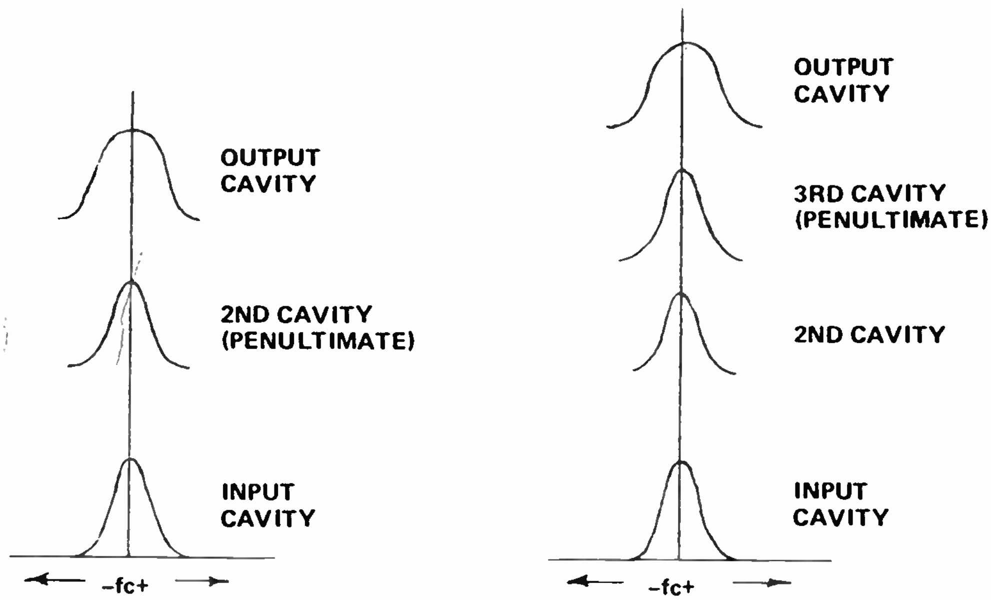


FIGURE 74: CAVITY RESONANCE FOR SYNCHRONOUSLY TUNED KLYSTRON

An electron that leaves the input cavity at zero time becomes the center of the partly formed bunch at the second cavity. This can be related to the center electron 1 (or 13) of Figure 66 shown earlier in the text. The rf voltage at the second cavity will have a phase that will retard the greatest number of electrons if this cavity is tuned to the input frequency. For this reason, the rf voltage at the second cavity will lag the voltage at the input cavity by an angle of 90 degrees.

Although the Applegate example of Figure 73 is not of a 4 or 5 cavity UHF-TV klystron, it should be easy to visualize the effect and improvement with additional intermediate cavities. Each subsequent cavity would improve the bunching in the same manner as just described, and you will also note that optimum bunching does not occur in the intermediate cavity; optimum bunching occurs at the output cavity.

If you again compare the Applegate diagram of Figure 66 for the two cavity klystron amplifier with that of Figure 73, it shows there are fewer electrons passing the output gap of the three cavity amplifier during the wrong half of the cycle when the field is transferring energy to the beam, and there are more electrons in the bunch. This means that the efficiency of a three cavity klystron is higher than that of a two cavity amplifier. For a 4 or 5 cavity klystron amplifier there would be of course additional improvement in the efficiency for the same reason; the beam is partly bunched at the second cavity and the additional velocity modulation at each intermediate cavity causes more electrons from the wrong half of the cycle to become part of the bunch (or current pulse).

> NOTE: It may be detrimental to operate some multi-cavity klystrons at saturated output while synchronously tuned because of the high gain and power. This is especially true of high efficiency tubes such as the 4 and 5 cavity UHF-TV klystrons. The high rf fields at the output cavity gap give rise to reversal of direction of the slower electrons reaching this point. Return electrons constitute electronic feedback within the tube structure. When the gain and power is increased to some critical level, the electronic feedback results in tube oscillation. The klystron manufacturer should be consulted regarding this type of operation.

A further increase in efficiency can be achieved if the penultimate cavity (second cavity in this example) is detuned on the high frequency side of resonance, so that the bunching action of the penultimate cavity is more nearly in phase with the bunching from the input cavity. Once the cavity is detuned, the rf drive power can be increased for optimum output power, which will yield a greater output, greater efficiency and some overall increase in bandwidth, depending on how far the penultimate cavity was detuned. Figure 75 pictorially represents a stagger-tuned (or broadband) klystron with only the penultimate cavity detuned and showing the relative positions of the bandpass of each cavity.

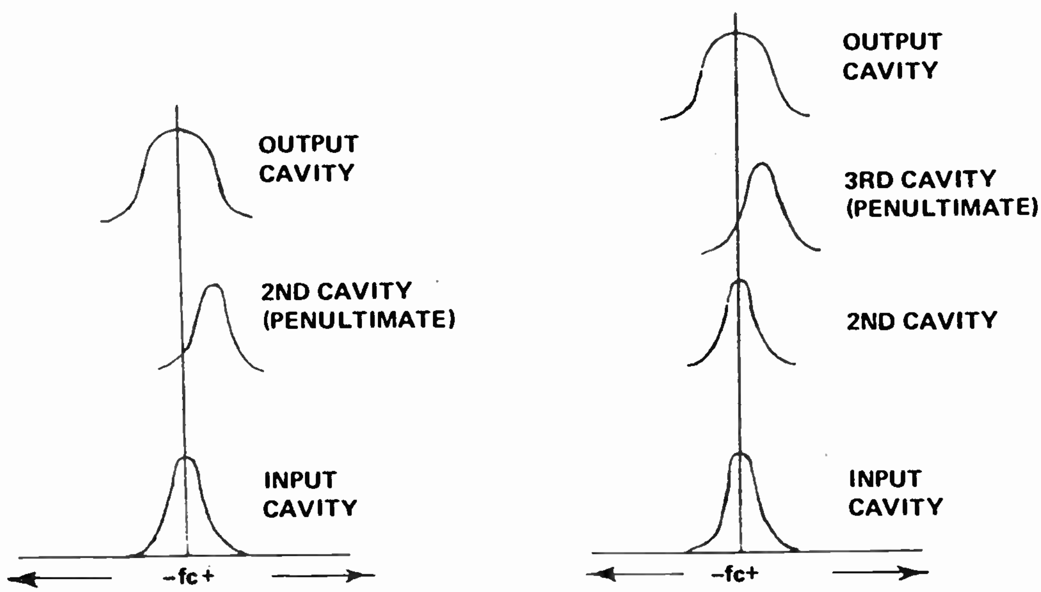


FIGURE 75: CAVITY RESONANCE FOR STAGGER TUNED KLYSTRON

When broadbanding a klystron amplifier, the most important cavity is the penultimate cavity. If this cavity were detuned to the low frequency side of resonance, this would lower the impedance of the cavity and in turn, the voltage induced in the cavity would be reduced until it was as small as the input cavity voltage (depending on how far the cavity was detuned). It will also shift the phase of the cavity voltage until bunching from the two cavities is almost cancelled. If the rf drive power were increased at this time, the rf power output may actually decrease or may only rise slightly because of incomplete bunching due to the phase of the voltage at the cavity. If you continued tuning incorrectly to a lower frequency, the voltage induced at the second cavity may be reduced to the point it had no effect on the beam and the output power would approach the level for a tube as a two cavity amplifier using only the first and third cavity (or 1st, 2nd and 4th of a 4 cavity amplifier). This effect is illustrated in Figure 76.

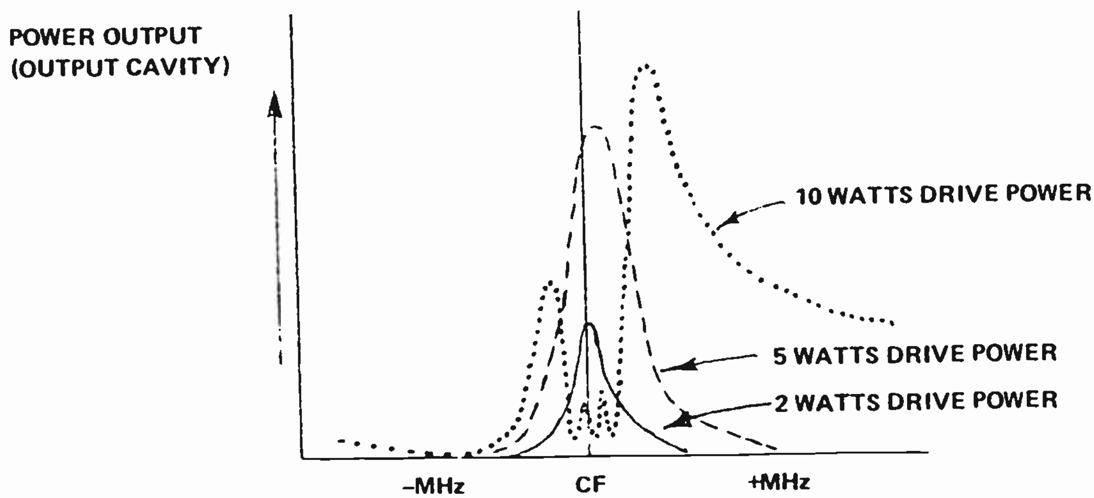


FIGURE 76 : EFFECT ON KLYSTRON POWER OUTPUT AS A FUNCTION OF PENULTIMATE CAVITY TUNING

The lower horizontal scale represents the detuning of the penultimate cavity around the center frequency indicated by CF. The verticle scale represents the power output from the klystron. I have arbitrarily choosen three drive levels for the example. The three curves show the lowest power where all three cavities are tuned to the same frequency (synchronous). The second curve represents the penultimate cavity tuned a little to the high frequency side of resonance and with some increase in drive power (dashed lines). The third curve shows the effect of tuning still further to the high frequency side of resonance instead, and with the same high rf drive level. The power would go through a drastic reduction, rippling a little at center frequency and would rise a little.

If the rf drive level were continued to be raised, thinking you were tuned correctly on the high side and were trying to achieve maximum power output from the klystron, the peak current at the penultimate cavity may be high enough to damage the cavity. Detuning a klystron in this manner is not correct and this high circulating current could possibly burn up a tuner and or melt the edges of a drift tube. If you have done this, which has happened occasionaly to some users of klystrons, the evidence of the burnt tuner or drift tube is enough to determine the tube was mistuned and not operated correctly. Tuning methods and characteristics will be covered in another chapter.

Detuning the penultimate cavity substantially higher than the center operating frequency will also decrease the impedance. In turn, the voltage induced at the penultimate cavity will also decrease, the bunching will decrease and the overall power output will decrease, but it makes the phase of the voltage more nearly the same as the input cavity, so some extra energy must be supplied to increase the bunching of the electrons again.

> NOTE: Detuning the penultimate 3rd cavity of a 4 cavity tube, makes the phase of the voltage closer to the 2nd cavity voltage.

The extra energy for rebunching is naturally supplied by increasing the rf drive power (after detuning the penultimate cavity). This increased rf drive power will cause a rebunching at the penultimate cavity which will result in an increase in power output and efficiency because; the rebunching at the penultimate gap is applied to the electrons that would not have become part of the electron bunch in a single-stage amplifier. As a result, more electrons are removed from the wrong half of the cycle and become part of the electron bunch. A graphic illustration of the effect of detuning the penultimate cavity on the high frequency side of resonance of a three cavity amplifier and increasing the rf drive for optimum bunching at the output cavity is shown in the Applegate diagram of Figure 77.

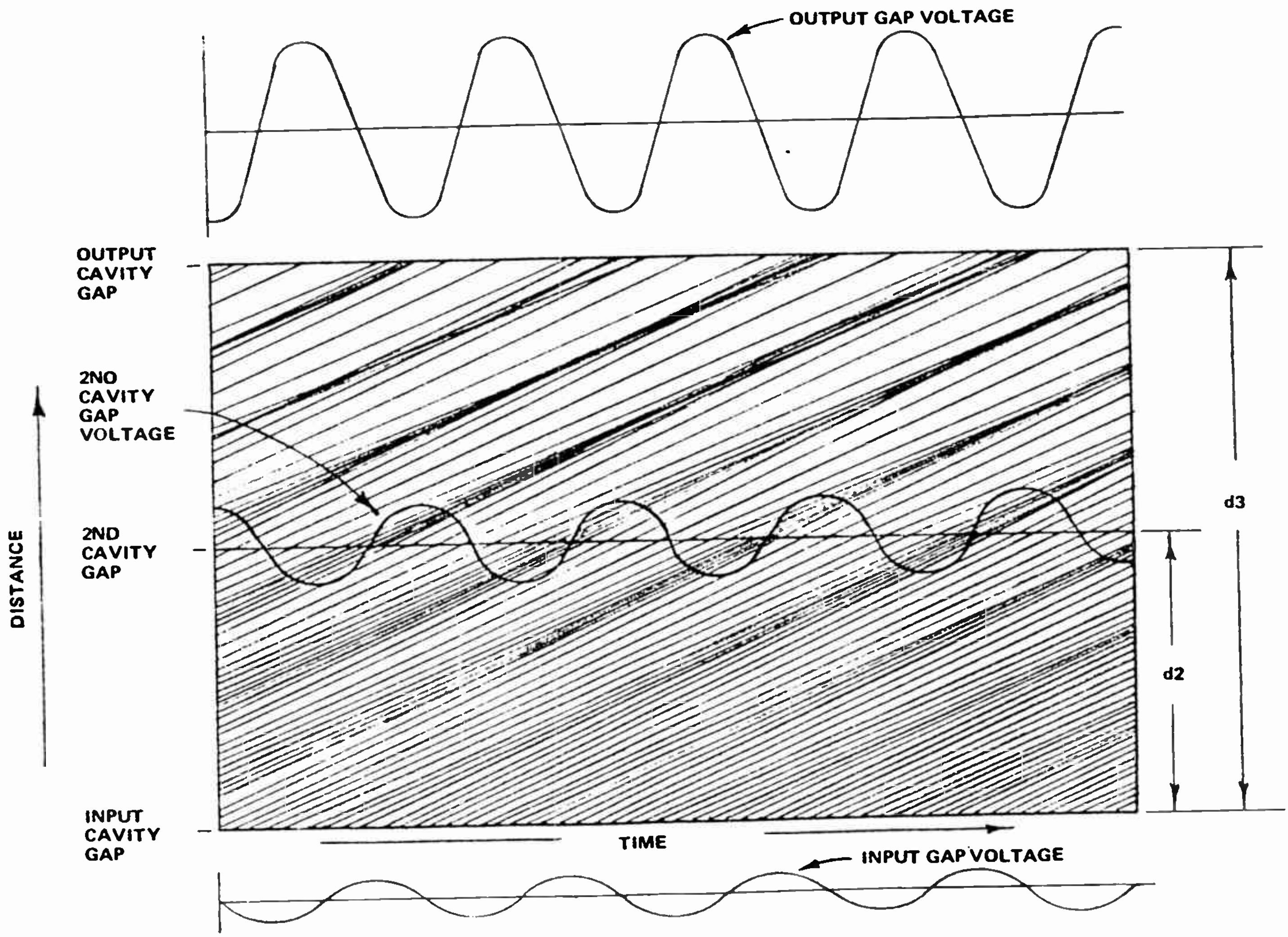


FIGURE 77: BUNCHING PROCESS IN MULTI-CAVITY KLYSTRON WITH INCREASED DRIVE POWER WHEN SECOND CAVITY IS DETUNED FOR BROADBAND OPERATION

In comparing the Applegate diagram of Figure 77 with that of Figure 73 for a synchronously tuned three cavity tube, you will note that the voltage at the input gap for bradbanding is greater because of the increased rf drive power. The penultimate cavity gap voltage also is shown in this example as being about the same after re-bunching, as Figure 73. Generally, when detuning the penultimate cavity, the voltage will be about the same or a little larger. You will also note that there is an increase in voltage at the output cavity indicating an increase in output power and efficiency.

Further broadbanding of this three cavity klystron example maybe accomplished by also detuning the input cavity slightly higher in frequency (but not as high as the penultimate cavity) and then readjusting the rf drive power again to rebunch the electrons for optimum output power. The bunching action would be similar to what has just been described. For further broadbanding of a 4 cavity klystron, the second cavity is usually tuned a little lower in frequency for shaping the bandpass along with the penultimate cavity tuned to the high frequency side. Figure 78 illustrates a broadband tuned klystron with the relative positions of each cavity for optumum bandwidth.

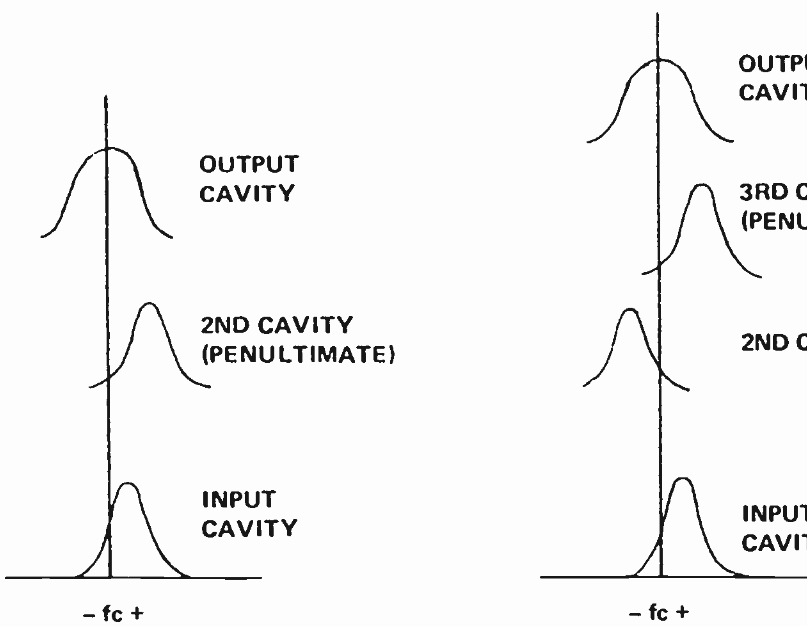


FIGURE 78 : CAVITY RESONANCE FOR BROADBAND TUNED KLYSTRON

It should be obvious by now how similar the bunching is in a two cavity amplifier as compared to a 3, 4 or 5 cavity amplifier. Optimum bunching (saturation) or over-bunching does not occur at the input cavity or any intermediate cavity. In all case, optimum bunching occurs at the output cavity. The overbunching condition as shown in Figures 69 and 70 are basically the same for a 3, 4 or 5 cavity amplifier too. The overbunching occurs just before the output gap, not at any of the intermediate cavities. The transfer curve of Figure 70 is also representative for all klystrons too and the power output peaks labeled Saturated and 2nd Power Peak are representative of the power out of the klystron under different values of rf drive power, not of any other cavity.

Overbunching and debunching will be discussed in more detail in the next section following.

5.5.2 Overbunching and Debunching

The conditions that cause overbunching and debunching and the space charge effects have been mentioned in the previous sections but no attempt was made at that time to expand on the detail problems associated with these conditions in order to present a more straight forward approach to the bunching phenomenon. However, the effects of these conditions are important enough to discuss them seperatly.

Overbunching is the condition which exists in a klystron when the drift space is too long or, what amounts to the same thing, if the input gap voltage and/or the accelerating beam voltage are too high. Since this text is not directly concerned with designing klystrons, we can assume it has been designed and constructed correctly and can at least discount that aspect of the definition, too long a drift tube, for this discussion.

The Applegate diagram of Figure 69 and throughout section 5.5 first described the effects of overbunching caused from overdriving a klystron with too much rf drive power or by having the beam voltage too high. It is unfortunate but many books and articles written about klystron operation do not always emphasize overbunching problems other than perhaps mentioning, do not overdrive a klystron. This forbidden statement usually never has an accompaning explanation as to why? Of course the more theoretical articles or text books do discuss the bunching and current distribution for an overbunched condition but this is generally to difficult for the new student or average user of klystrons to extract any practical and usefull information. On the following pages are a few examples of overbunching and debunching problems that can be easily related to.

An important fact to remember in klystron operation is the electron transit time, which is related to beam velocity and thus to beam voltage. Using a fixed value of transit time or beam voltage (other than the change in velocity due to rf drive power and velocity modulation) is usefull in describing klystron operation. This approach was used in all of the previous section on bunching, but if there is an electron velocity change due to a change in beam voltage, there is a change in phase of the rf driving current (or bunching). Any change in beam voltage, while the rf drive level and or cavity tuning are held constant, creates changes within the klystron that are quite complex. Some of the changes or major effects that result from lowering or raising the beam voltage are as follows;

1. Beam Velocity, beam power
2. Electron transit time through the cavity gap and drift tubes, bunching
3. Gain, efficiency, power output.

The amount of noticable change that would effect operation will of course depend on how much the beam voltage is varied and this could vary from a given tube type to another. Users of klystrons that have a mod-anode as part of the electron gun, and this includes UHF-TV klystrons, have the additional mod-anode voltage to be aware of. Theoretically the cathode to mod-anode voltage does not effect the beam velocity through the rf circuit, it only controls the total current the tube will draw. The cathode to body voltage effects the beam velocity through the rf circuit. However, there is another secondary effect if the mod-anode voltage is changed from the normal operating level. The mod-anode voltage changes the current and thus the perveance of the electron gun, and the perveance is related to bandwidth.

NOTE: The definition of perveance was first described in Section 2.2.5. Here again, the amount of perveance change which will effect operation will vary by how much the mod-anode voltage is varied from the 3/2 power relation. Perveance and bandwidth will be covered later in the text.

If a klystron is operated at some lower beam voltage other than what is specified for normal operation, for one reason or another, such as for initial tune up for synchronous or broadband operation, this in itself is acceptable and is often done for safety and protection of the tube. Many UHF-TV klystron users have facilities for approximately a 33 percent reduction in beam voltage for initial tune-up or just low power operation and aging of a spare tube before operating at full service. However, one must be aware that with the reduced beam power it will require a little more rf drive power to achieve either a given amount of power output or given bandwidth. There may also be a frequency shift of the cavities due to the change in beam loading of the cavities.

What happens is that effectively the drift tubes appear longer electrically because of the reduced beam voltage and beam velocity, and consequently will require more rf drive power to approach optimum bunching. A common error at this time by many operators is to raise the beam voltage to the normal operating point after the initial tune up but neglet to either retune the tube or readjust the rf drive power properly.

NOTE: The manufactures tuning instructions for the transmitter and klystrons do not necessarly emphsize this point but if followed closly there should be no problems.

A substantial increase in beam voltage changes the beam loading of the cavities and thus the frequency of the cavities. If the tuning and or rf drive are not checked and corrected also, the tube may be in an overbunched condition caused by the increase in beam voltage and the higher rf drive power that was applied during the low voltage operation. Both tuning and the rf drive level must be checked for proper operation.

In this overbunched condition, not only will the bandpass be distorted, the power output of the tube would be lower than normal and the phase shift through the tube may be enough to cause distortion of the intelligence being transmitted. Usually one error is compounded by another, and at this point quite often an operator will increase the rf drive power because the power output of the klystron will be lower than normal due to the overbunching and or detuned cavities. If this approach is continued, the power output will continue down and perhaps by this time the tube may be damaged or destroyed. The most detrimental effect is caused by the excessive rf drive power applied to the tube. Since each intermediate cavity has an increasing effect on the bunching and peak current at each cavity, the penultimate cavity will have a very high circulating current which could burn or destroy the tuner or may melt the edges of the drift tubes (see Figure 79). The tuner shown in Figure 79 was removed from the penultimate cavity of an internal cavity UHF-TV klystron. It visably shows a burnt portion of the bellows and a hole which resulted from the excessive current in the cavity, allowing the tube to be open to air. External cavity klystrons would have similar damage with possible arching at the contact finger rf seals which would result in a puncture of the cylindrical ceramic or metal seal that surrounds the vacuum portion of the drift tube.

How is this high current generated when the output cavity is in an overbunched condition and the power output is low? As you should recall, overbunching occurs just before the output gap, there is no overbunching in any other cavity. When excessive rf drive is applied to the input cavity, each successive intermediate cavity has an increase in the current pulse (bunching), consequently the penultimate cavity will have an extremly high current.

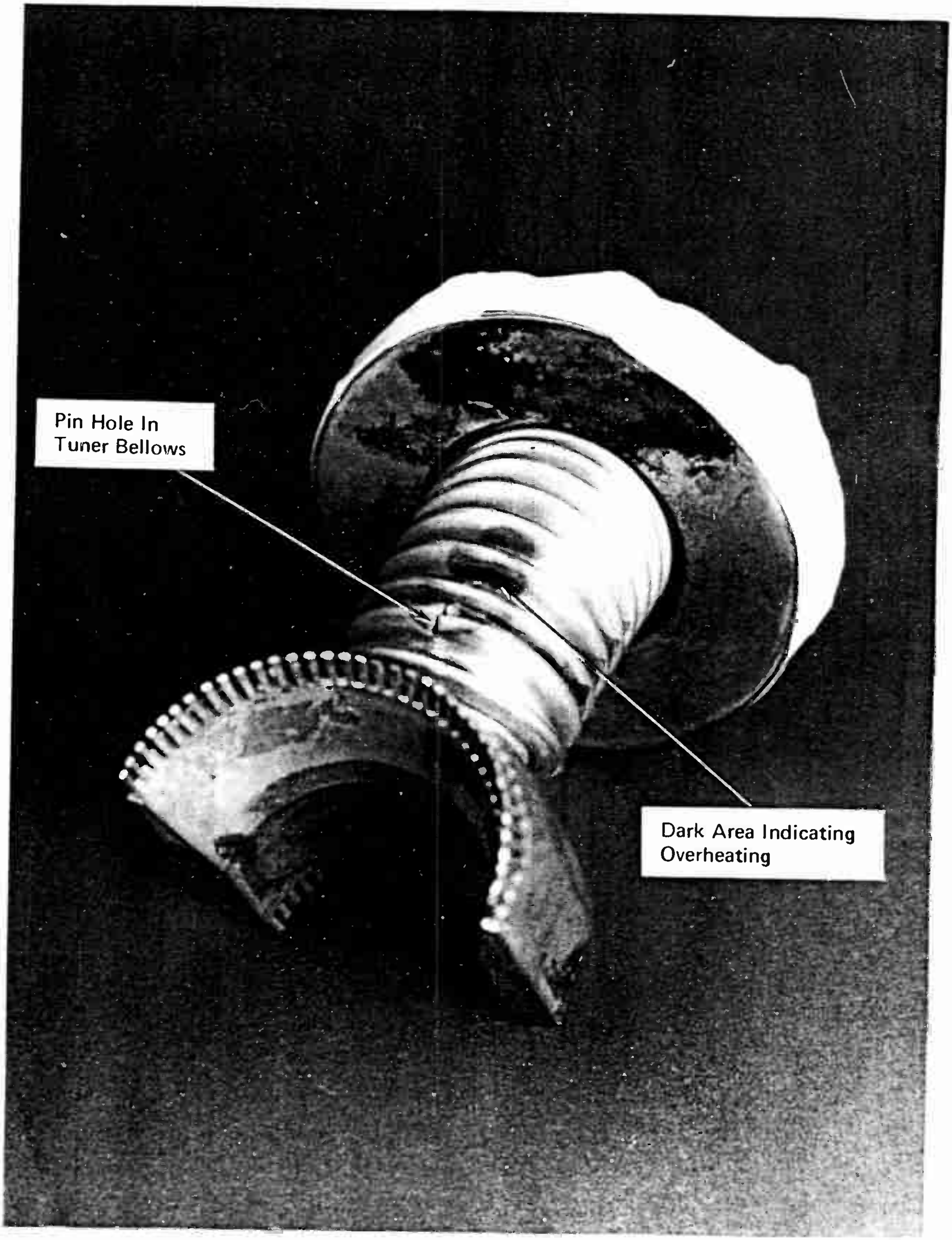


FIGURE 79: DAMAGED TUNING PADDLE FROM INTERNAL CAVITY UHF-TV KLYSTRON
Photo courtesy of Varian Associates Inc.

The behavior of these conditions in the above example of overbunching can be illustrated by constructing a diagram similar to the diagram used to explain the operation of a Class A Triode Amplifier. Figure 80 is a variation of that approach, where the construction of the diagram or graphs if you prefer, show the relation between the input gap voltage, the tuning of the input cavity frequency and the power output of a klystron at a fixed beam voltage.

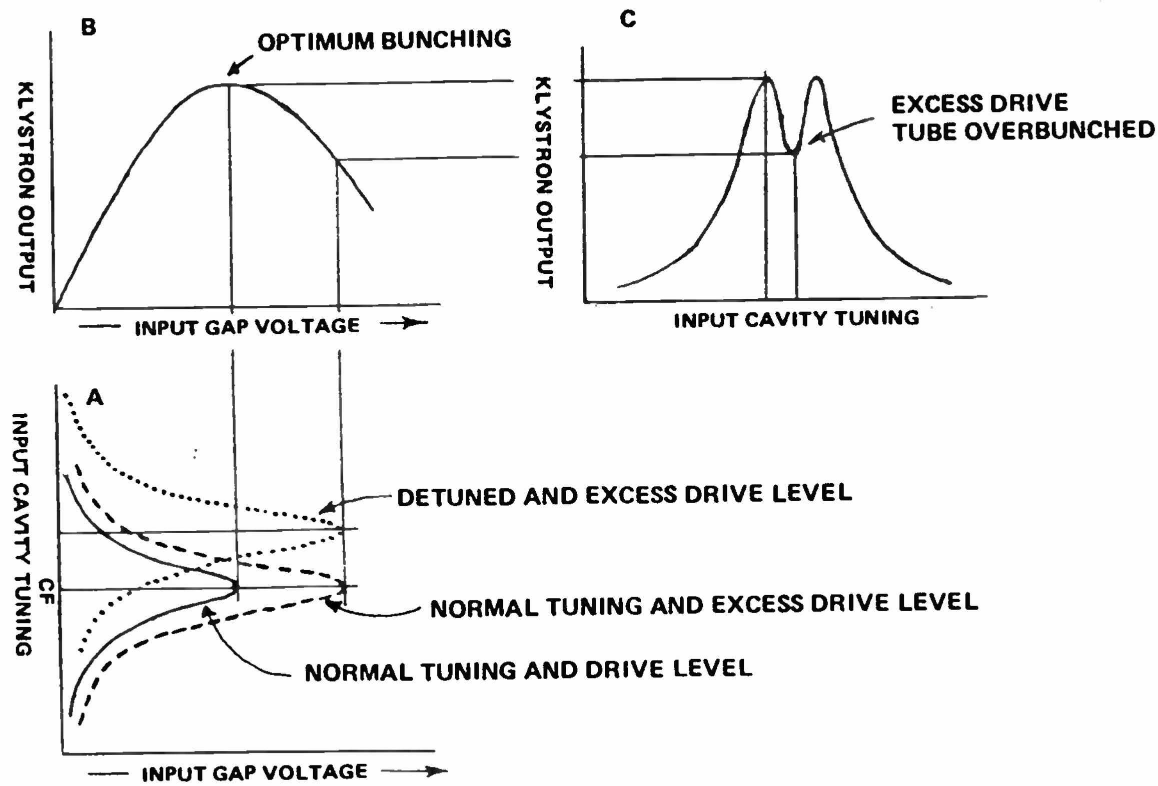


FIGURE 80: EFFECT OF CHANGING TUNING OF A KLYSTRON AMPLIFIER AND DRIVE LEVEL RELATED TO THE BUNCHING CHARACTERISTICS. NORMAL FIXED BEAM VOLTAGE

The graph implies a two cavity klystron because the intermediate cavity frequencies can not be shown in this type of presentation. This is no problem, as the input cavity tuning or frequency shift is representative of the effect of the intermediate cavities and of course the inportant item in overdriving any klystron is the input gap voltage.

Graph A of Figure 80 has 3 curves representing different sets of conditions of input cavity tuning, above and below some resonance point, and input gap voltage which is a function of the rf drive power. Graph B is a transfer curve similar to Figures 70 and 72 which were explained in section 5.5 and 5.5.1. The single curve is a plot of power output from a klystron as a function of the input gap voltage variation. Graph C is now a composite showing the effect on the klystron output when the input gap voltage and or tuning are varied.

Let us now examine the curves that result when different points are transferred from graph A to B to C. In graph A the solid line curve represents normal tuning, the peak of this curve when transferred to curve B shows it to be at the peak of the plot. This represents saturated power output which is achieved when there is optimum bunching. From the peak of curve B to the peak of curve C, the line again extends to the peak.

Looking again at graph A, the dashed line curve represents normal tuning but the input gap voltage or rf drive power has been increased. When the peak of this curve is transferred to curve B, it falls at the overdriven point on the transfer curve where the power output has decreased. Extending the line to curve C, shows the typical double-peaked output characteristic of an overbunched klystron amplifier. The third curve in graph A (dotted line) could be representative of the example explained earlier where tuning had been done at low voltage and then having the operating voltage raised to normal operation. This dotted line curve in A shows the cavity detuned and with excessive gap voltage. When the peak of this curve is transferred to B and to C, the result is similar to the previous example for normal tuning and a high input gap voltage.

Another problem that accompanies an overbunching condition is high body current. The high body current is created in the vacinity of the penultimate cavity because of the excessive input rf drive power creating a high peak current at the cavity and additional electron interception. The electron bunches at this point have been made very dense and because of the mutual repulsion of each electron, there will be stray electrons that will tend to leave the bunch, striking the drift tube walls. This is what would sometimes give the appearence of a boloney or bulge in the electron beam. It is interesting to note, if in an exaggerated example, the voltage developed at the penultimate cavity were large enough to bring the electrons to rest or slowed their velocity to nearly zero as they crossed the gap, the electrons would tend to move sideways striking the drift tube.

Closly related to overbunching is debunching. This condition is encountered because of electrostatic forces that exist between neighboring electrons in the beam. This is a space charge effect as mentioned earlier. It does not necessarly happen when the tube is in an overbunched condition. Space charge forces oppose the formation of electron bunches and can be resolved into two catagories. One tends to destroy the focus of the beam and is called transverse debunching, and the other repls the electrons that would become part of the bunch and reduces the bunching action is called longitudinal debunching.

The effect of transverse debunching is to reduce the efficiency of the klystron because many of the electrons from the bunch become lost on the walls of the drift tubes. There is also an excess of positive space charge in the region between bunches. This positive space charge may force electrons, which would normally be lost owing to divergence of the beam, back into the beam during the wrong part of the cycle when they would subtract additional energy from the output cavity. Therefore the effect of transverse debunching is not limited to the loss of electrons from the bunch itself. The transverse debunching can be eliminated by using a strong longitudinal magnetic field to prevent divergence of the beam. Klystrons using large electromagnets such as the UHF-TV klystrons, should have no problems with this form of debunching provided the magnetic circuit is functioning correctly.

Longitudinal debunching has the effect of reducing the bunching action and therefore reduces the gain of the klystron. If for example, the area around a given electron starts to become more and more thickly populated because of a prearranged bunching action, as that population increases so does the repulsive forces in the area. Near the center of a bunch there will develope forces that are proportional to the distance of a particular electron from the center of the bunch. The resultant action is similar to that observed in mechanical compression problems. Assuming one could view these electrons approaching the center of the bunch in both directions, these electrons will be progressively slowed down as they approach the center of the bunch because the electrostatic forces will build up. As a result, the individual electrons before and after the center of the bunch will approach to within a given distance of the center and will then turn and move away from it. This action can be roughly illustrated by the use of a Applegate diagram (see Figure 81). The electrons near the center of the bunch approach each other and then diverge without crossing. Compare Figure 81 with that of Figures 66, 73 and 77 for normal bunching.

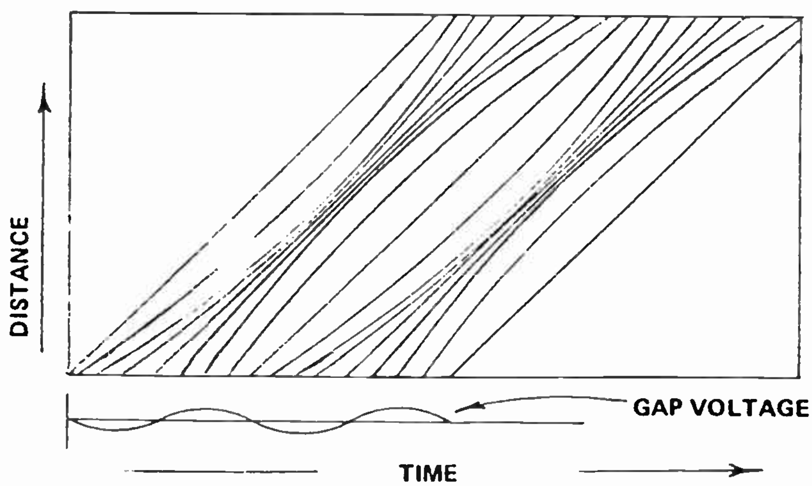


FIGURE 81 : APPLEGATE DIAGRAM SHOWING SPACE CHARGE DEBUNCHING

Since the space charge repulsion forces near the edge of the beam are less than at the center, the bunches will tend to form sooner near the edge and be more intense. As a result the bunches will tend to be oval or crecent shaped in a plane through the axis of the beam, with their concave side toward the electron gun. The Applegate diagram of Figure 81 is then illustrated as in Figure 82. As you can see in Figure 82, as the bunches tend to form, the space charge density in that region will increase and the radial expansion will be greatest about a bunched center. Portions of the beam between bunches explode radially.

This longitudinal debunching can be overcome within certain limits, by increasing the drift tube length. However if the distance becomes too great, the debunching forces act during a longer interval and it may be impossible to bunch the electron beam. For this reason, there is an optimum drift distance and a maximum gain which can be obtained with a klystron amplifier.

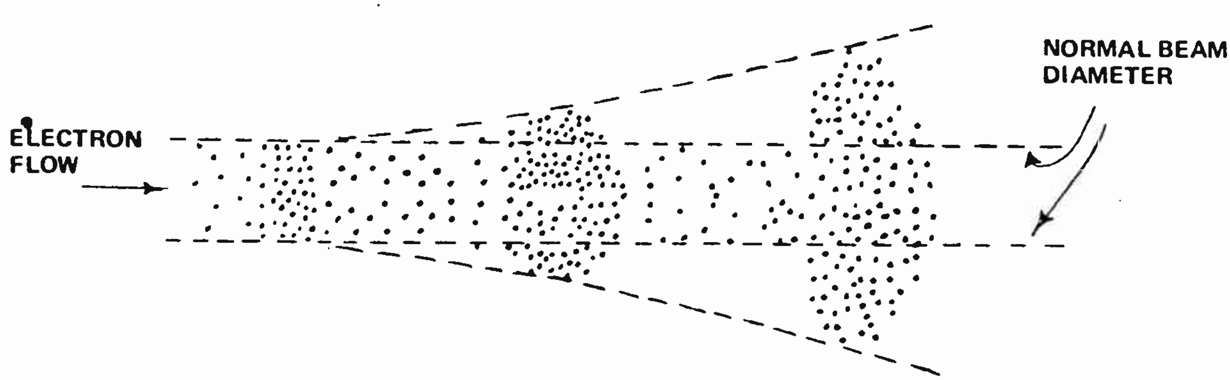


FIGURE 82: BUNCHED BEAM SHOWING RADIAL DISPERSION (DEBUNCHING) DUE TO SPACE CHARGE

6.1 General

Collectors are used on klystrons and other similar microwave tubes to dissipate the power remaining in the electron beam after it passes through the output cavity. The basic function of a collector is the same as an anode (or plate) in a diode or triode vacuum tube; they both must be capable of dissipating a certain amount of heat generated by the electron beam. A typical linear beam tube such as a klystron, must convert and dissipate 50 to 80 percent of the dc input power into heat; consequently a substantial amount of cooling of the tube's components must be provided. Obviously, most of the cooling is required by the collector, although some cooling is necessary for the rf structure because of intercepted beam current and rf losses.

There are numerous varieties of collector designs with cooling accomplished by convection, conduction, forced air, vapor phase, heat pipe and forced liquid cooling, in the order of increasing dissipation density capability. Although, for a given collector area, the order of increasing heat transfer effectiveness is as follows:

radiation and natural convection cooling;
forced air cooling;
forced liquid cooling;
liquid evaporation or vapor phase (heat pipes).

The simplest cooling, of course, is by radiation and conduction which occurs simultaneously. This method of cooling large klystron collectors obviously is not practical as a primary method, although there is always a certain amount of radiation and conduction of heat from the tube body and collector to the surrounding area. There are a number of limiting factors with this cooling technique; however, it is a method that is used for many small, low-powered reflex klystrons when it is feasible.

Forced air cooling is more effective, but it is also a little more complicated to implement than radiation cooling because of the added fans, temperature sensors and control systems. Many small klystron oscillators and amplifiers also use this method of cooling both collector and body. Some of the most recent designs of high-powered, air-cooled-klystron amplifiers have collectors capable of dissipating up to 30 KW of power. However, because of the lower tolerance power density of air cooling, they are generally larger than comparable water-cooled varieties. This method has its practical limitations: such as, when the collector is made larger, so must the blower system be enlarged.

Forced liquid cooling has a much greater magnitude of heat transfer per unit area than the previously mentioned systems and is the most common cooling method for linear beam tube collectors. With a greater heat transfer capability, the system becomes more complex with the addition of a pumping, filtering and control system. The amount of heat that can be transferred to the liquid coolant is proportional to the wetted surface area, the heat transfer coefficient, and generally, an operation at a high velocity flow.

Liquid evaporation or vapor phase cooling provides the greatest rate of heat transfer per unit area yet mentioned and is becoming more popular where it is necessary to cool collectors with high power densitites. Cooling is accomplished by allowing the coolant at the collector surface to boil. The steam generated is then condensed in a heat exchanger and returned to the collector. This system must also have water lines and steam lines similar to the forced-liquid-cooling system. The total coolant flow rate is considerably less than a comparable forced liquid cooling system, but it does operate at a higher coolant temperature. The system can be simplified a little; it can be designed without the use of a coolant pump, if desired.

Heat pipe cooling is similar to evaporation cooling with the exception that the cooling structure is a tube that is first evacuated, then the coolant is put inside and the tube sealed from air. Heat is transferred by evaporation of the liquid at one end of the pipe or tube. The vapor transports the heat to the end of the pipe which is cooler, through an inner structure that functions like a capillary tube. At the cool end the liquid condenses and transfers the heat to a finned radiator attached to the outside of the cool end.

No matter which of the above five basic methods are used for cooling a collector, the basic electrical operation is the same.

We will now consider the operation and basic construction of the two most commonly used collectors on UHF-TV klystrons, the forced liquid cooling and the vapor cooled system. These collectors are made of copper in the form of a large cylindrical tube and are attached to the tube body of the klystron with a large ceramic insulating ring. The ceramic ring is metalized on the top and bottom surfaces with a seal ring brazed in position. The seal ring is then sealed to the tube body and collector, forming part of the vacuum seal.

6.2 Forced Liquid Cooled Collectors

The mechanical design of forced-liquid-cooled collectors may vary from one manufacturer to another and the size will vary according to the amount of power dissipation required. Typical of the many forced-liquid-cooled-collector designs for UHF-TV klystrons is the one pictured in Figure 83 with the outer coolant manifold removed, showing the grooves or channels cut into the outer wall which increase the surface area and aid in directing the coolant flow. A cutaway view of the same type collector is shown in Figure 84, illustrating the direction of the coolant path when the outer manifold is installed. The inside of the collector core is a smooth, machined surface, tapering to a point at the top. This type, or similar mechanical designs, are used on many of the external cavity UHF-TV klystrons and operate at a rather high coolant flow rate. According to the power capability and the class of service, aural or visual, the flow rate may be between 15 to 40 GPM and with a resultant system pressure between 10 to 20 PSI. The klystron manufacturer's specifications should, of course, be consulted before operation.

Generally the coolant liquid should be distilled water which is chemically stable and has a high heat transfer capability. However, an antifreeze mixture such as ethylene glycol and water or Coolanol 45 can be used if there is an extreme need for protection against freezing.

CAUTION: Before using any antifreeze mixture for cooling a klystron collector or body, the manufacturer of the klystron should be consulted for specific recommendations, since antifreeze solutions have lower cooling capabilities than water and may damage the tube and void the warranty.

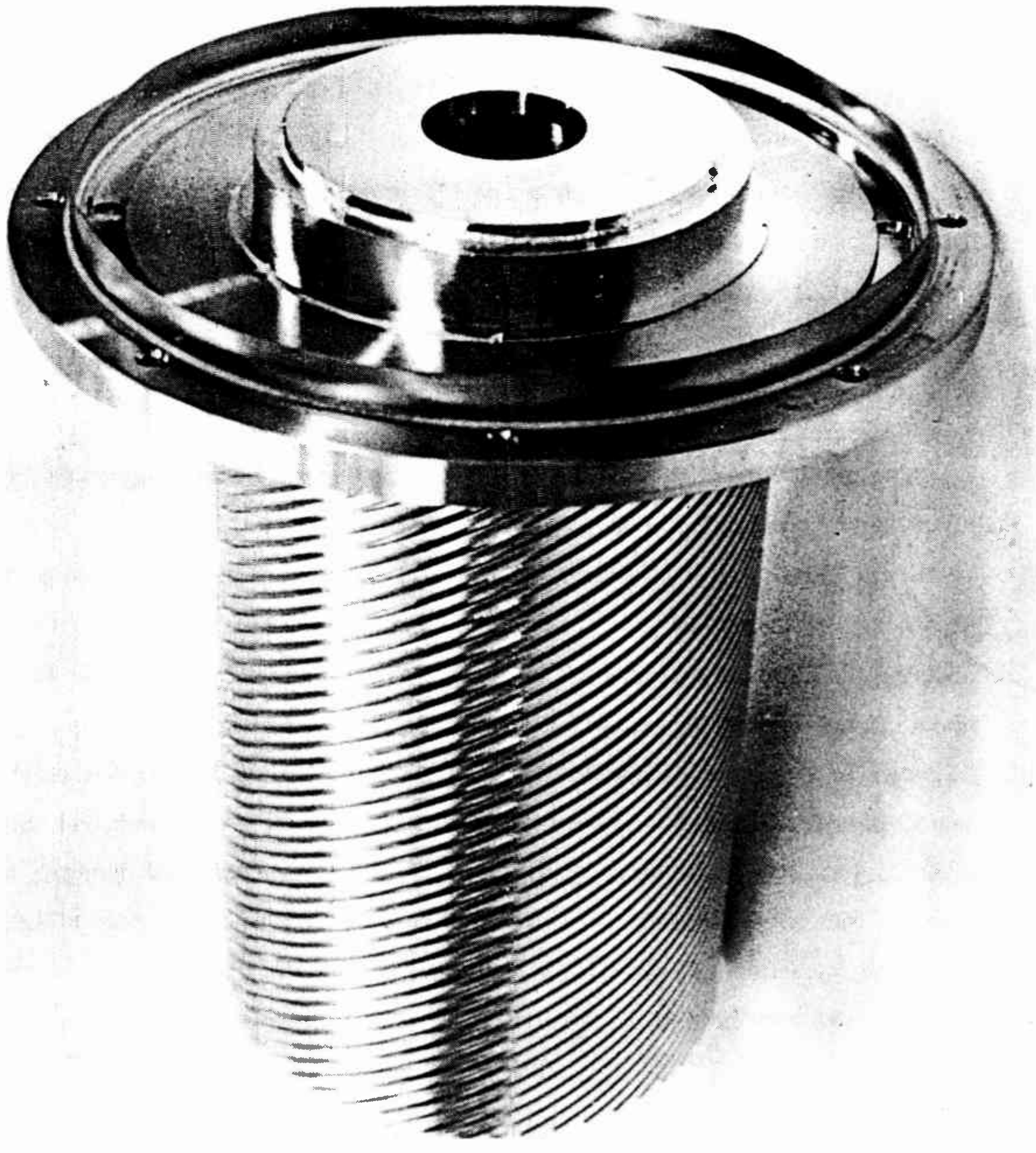


FIGURE 83: TYPICAL FORCED LIQUID COOLED COLLECTOR CORE, USED WITH EXTERNAL CAVITY UHF-TV KLYSTRON
Photo courtesy of Varian Associates Inc.

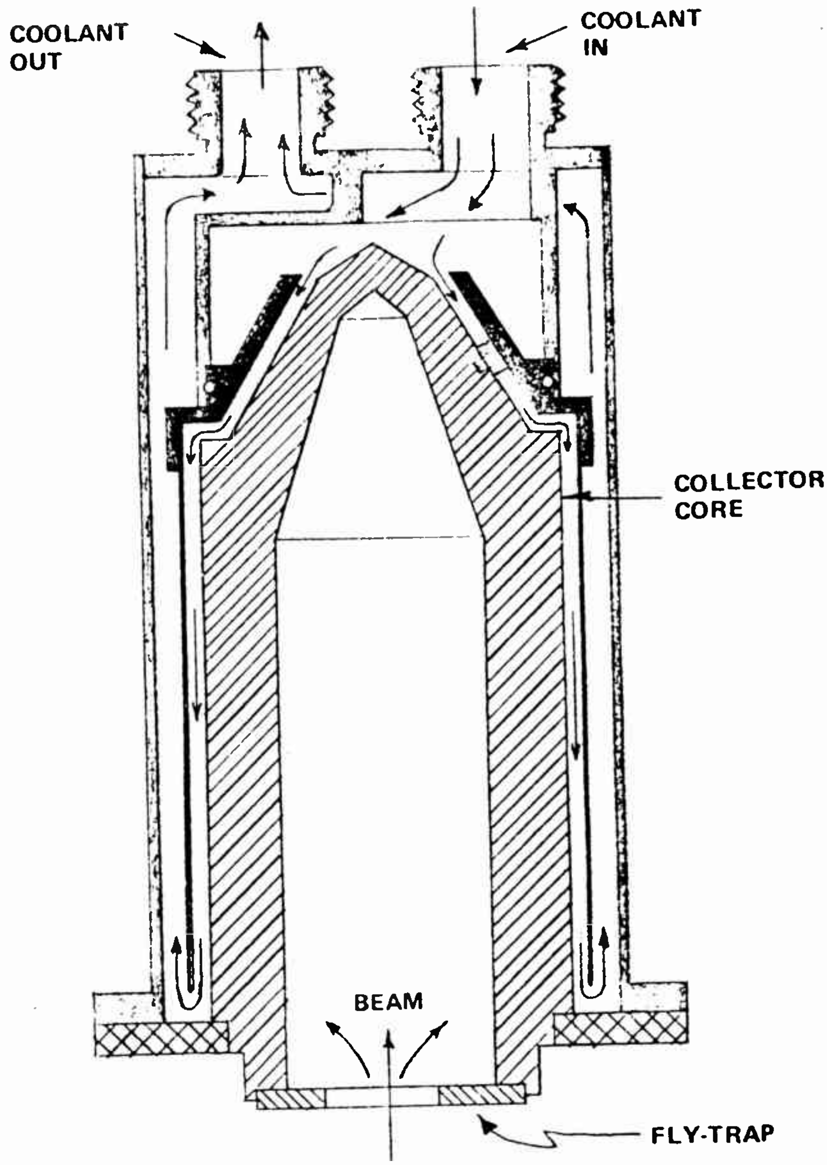


FIGURE 84 : TYPICAL FORCED LIQUID FLOW COOLED COLLECTOR

Generally, most forced-liquid-cooled collectors are designed to operate under turbulent flow rather than laminar flow conditions (laminar, streamline flow). At lower flow rates in the laminar region, the liquid flows in smooth layers along the surface and grooves of the collector and does not mix between layers, consequently the heat transfer is not efficient. When the flow rate is increased, the liquid becomes turbulent, breaking up the smooth layers and, in turn, the heat transfer capability increases significantly.

The transition between laminar and turbulent flow depends both on the type of coolant used and the geometry of the coolant flow paths. The limiting factor on minimum flow rate is that the collector must operate below the boiling temperature of the coolant, otherwise steam may form in the cooling path and may increase the already high operating flow pressure. This increase in pressure could result in a ruptured collector or coolant lines and/or a burned collector from the lack of coolant. The laminar and turbulent flows are illustrated in the graphs of Figure 85. The graphs are generalized, as each collector design would present a slightly different set of conditions.

A typical example of a burned and melted collector is illustrated in Figure 86. The view is looking into the opening at the base of the collector. The destruction illustrated could happen on either the forced liquid cooled collector or the vapor-cooled collector (refer also to Figure 90).

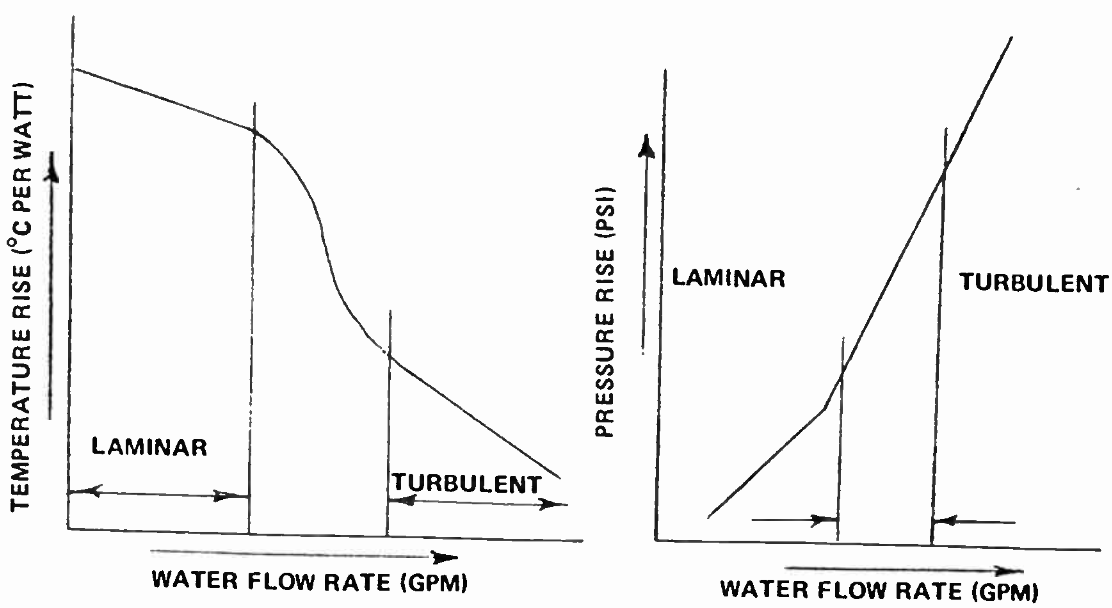


FIGURE 85 : TEMPERATURE RISE AND PRESSURE DROP RESPONSE AS A FUNCTION OF WATER FLOW RATE FOR FORCED LIQUID FLOW COLLECTOR

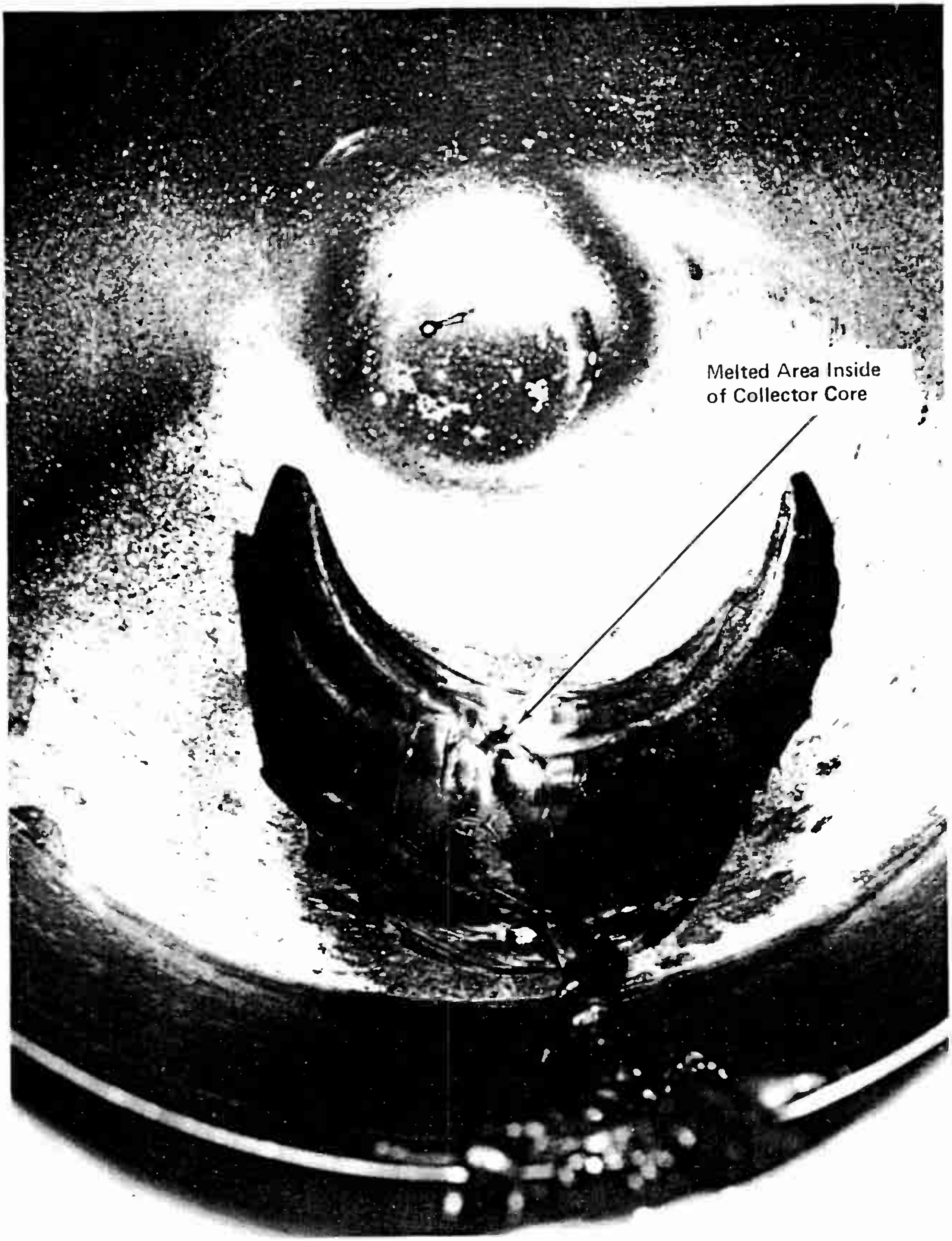


FIGURE 86: INSIDE VIEW OF A BURNED AND MELTED COLLECTOR
Photo courtesy of Varian Associates Inc.

6.3 Vapor Phase Cooled Collectors

Vapor phase cooling is not a new concept for cooling electron tubes, the first practical application was demonstrated in 1951.[8] However, it was many years later before it was utilized to any great extent as a means of cooling klystron collectors. Vapor phase cooling takes advantage of the latent heat of water evaporation by allowing boiling at the surface of the collector. The boiling is converted to steam and is then condensed in a heat exchanger and returned to the collector.

Vapor cooling has several advantages over other heat transfer methods. Among the most notable are:

- A: Maximum heat transfer capability (power density) of approximately 800 watts/inches^2 of the component's surface
- B: Water coolant for maximum heat transfer
- C: Stabilized operating temperature because boiling occurs at a constant temperature
- D: Collector cooling system will operate at a considerably lower flow rate compared to the forced-liquid-cooled collector
- E: Coolant system can be designed to operate without a pump if desired, although most systems use a small pump.

The surface of a vapor cooled collector in contact with the coolant is generally shaped with protrusions over a portion or all of the surface (See Figures 87 and 90). These protrusions or grooves aid in the escape of the vapor in order to prevent runaway boiling. They constitute obstacles which break up and scatter the vapor curtain created when boiling occurs.

8 "Vapotron Operation," by C. Beurtheret, Chief Engineer of the Electronics Group C.F.T.H., September 1, 1957

Distilled or demineralized water is the best choice for a collector coolant because it has several times greater heat transfer capability than the best dielectric fluids and is the best choice for UHF-TV klystrons. Dielectric coolants such as ethylene glycol have been used in some vapor cooled systems (notably external-anode-gridded vacuum tubes such as triodes or tetrodes), but at a considerable reduction in heat transfer capability. For this reason it is generally not recommended for use with UHF-TV klystrons. In using a dielectric fluid, the cooling system would most likely have to be completely sealed to prevent the oily-like vapors from escaping and settling on surrounding equipment.

CAUTION: A dielectric antifreeze solution is not generally recommended for klystron-vapor-cooled collectors. Do not attempt to use it without consulting with the tube manufacturer.

A typical vapor-cooled-collector design used on UHF-TV klystrons is pictured in Figure 87 and a cutaway view of a similar collector is illustrated in Figure 88 with the outer coolant housing installed. This is often referred to as a boiler housing. The inside of the collector is a smooth surface, tapering to a point at the top. The vapor-cooled collector has been used predominantly on internal cavity UHF-TV klystrons; however, the concept is by no means restricted to these tubes, as some manufacturers have used them on external cavity UHF-TV klystrons.

The operation of a vapor-cooled collector is not as straightforward as a forced-liquid-cooled collector. The volume of the coolant is rather low compared to a forced-liquid-cooled-collector design of comparable power, typically 2 to 2.5 GPM, which is quite adequate in maintaining the height level of the coolant in the boiler housing for operation.

CAUTION: Specific manufacturer's recommendations should always be followed for coolant operating level.

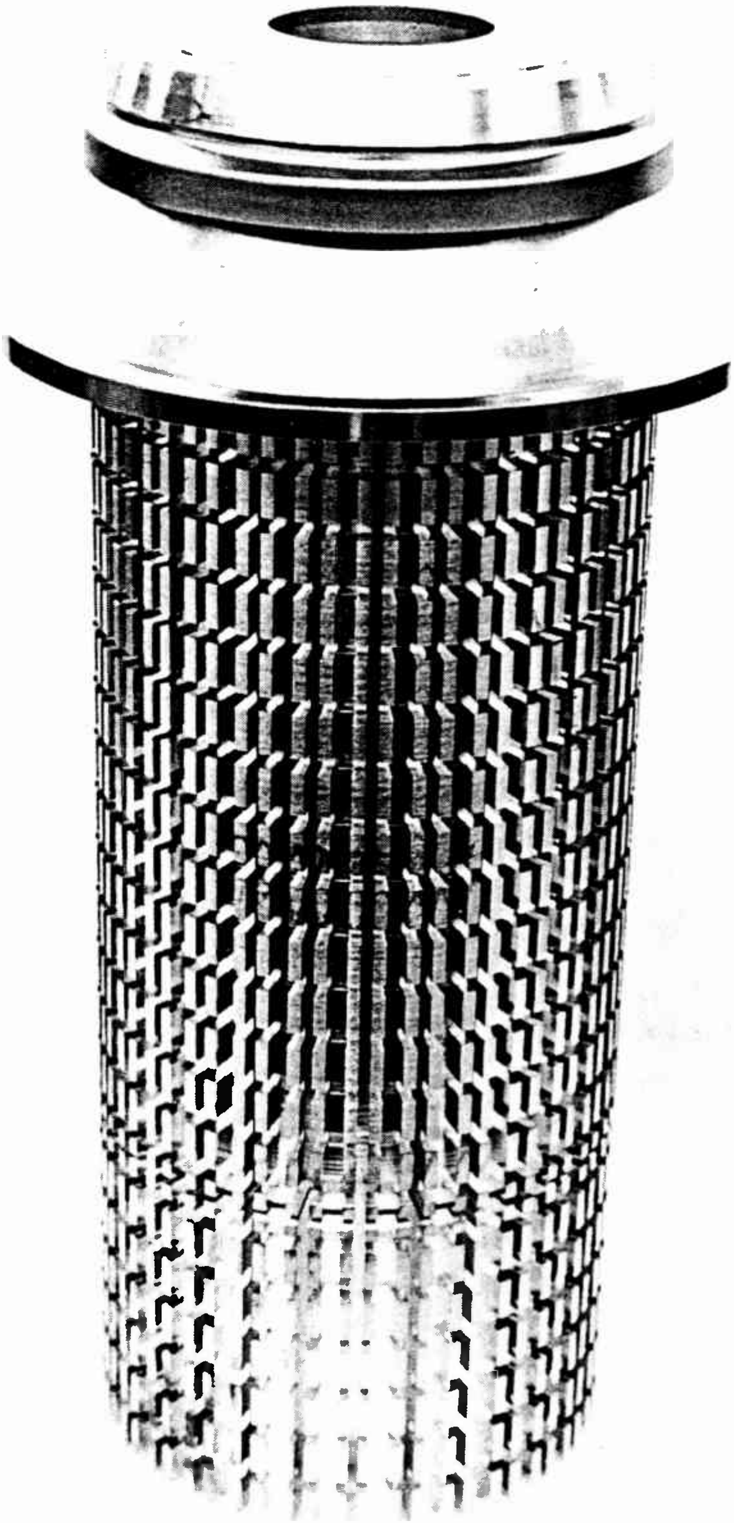


FIGURE 87: TYPICAL VAPOR COOLED COLLECTOR CORE, USED WITH INTERNAL CAVITY UHF-TV KLYSTRON
Photo courtesy of Varian Associates Inc.

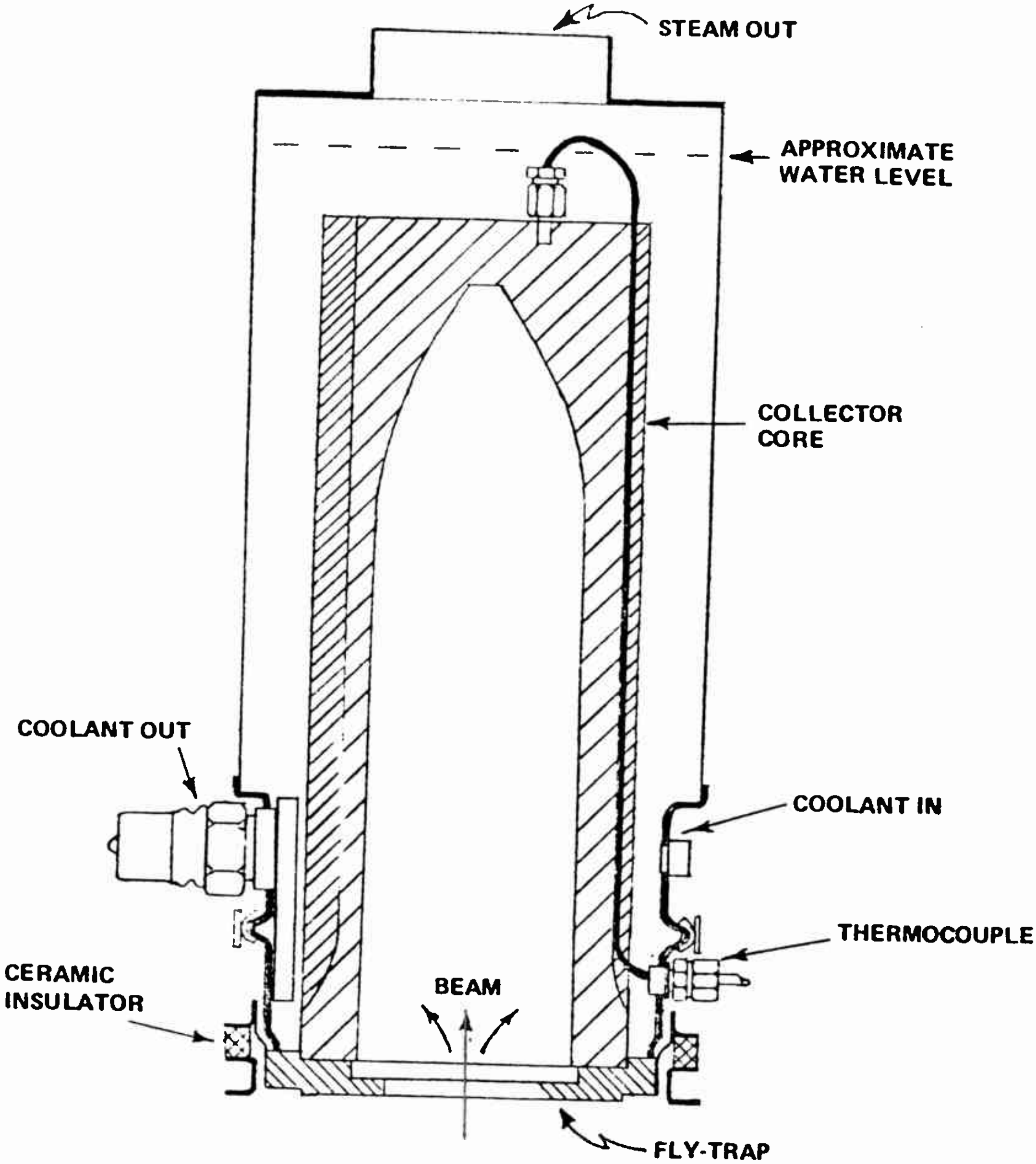


FIGURE 88 : TYPICAL VAPOR COOLED COLLECTOR

Vapor-cooled collectors can be designed and constructed in a variety of shapes and sizes according to the application and power level desired. Some of the many design considerations are: the type of cooling fluid to be used, collector surface configuration, cooling fluid condenser, pressure and equalization and tube orientation.

The collector surface and size is predicated in part on the amount of power dissipation desired and the system must operate at atmospheric pressure for the maximum heat transfer capability. This type of collector is usually operated in the collector up orientation although there have been vapor cooled systems designed for a collector down orientation.

The maximum power that can be transferred from the collector surface (in watts per inches^2 of collector surface) is approximately 800 watts as shown in the graph of Figure 89. This curve is often referred to as a Nukiyama[9] curve which has been published in various books on heat exchange.

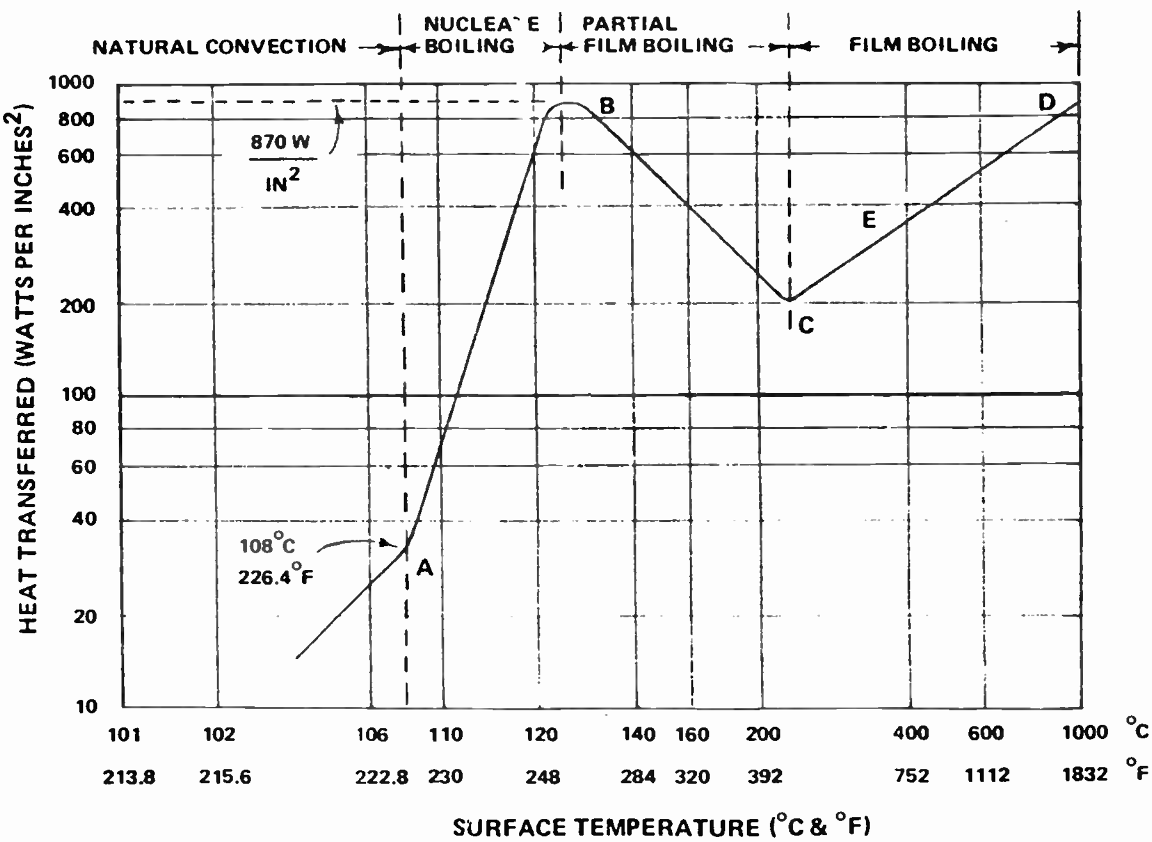


FIGURE 89 : HEAT TRANSFERRED PER UNIT AREA OF COLLECTOR SURFACE vs COLLECTOR SURFACE TEMPERATURE FOR EVPORATION COOLING WITH WATER

[9] Early Studies of Heat Exchange by Mr. Nukiyama was published in the "Journal of the Society of Mechanical Engineers," Japan, 1934

Most of the published curves have the same general aspect as shown in this graph and differ only because of variations in experimental conditions of the authors. This curve holds true for all power levels of vapor-cooled tubes when the cooling fluid is water and the tube operates at atmospheric pressure. In other words, a 30 kW variety UHF-TV klystron with a collector power of approximately 83 kW and a 55 kW variety klystron with a collector power of 150 kW, will both follow the curve of Figure 89.

The curve shows that when the collector surface temperature is below the boiling point of water the heat is transferred by natural convection without boiling. This is due to the heated water rising to the surface, being replaced by cooler liquid, causing convective liquid currents which provide the heat transfer without vapor bubbles.

If the collector surface temperature continues to increase, the natural convection heat transfer also continues to increase until the temperature of the collector surface reaches a few degrees above the boiling point of water, at 108°C, where evaporation cooling begins. The temperature range between 108°C and 125°C is called the nucleate boiling region. When the temperature of the collector surface reaches this region, small vapor bubbles begin to form at the collector surface as the water is boiled. They break away from the surface, and rise to the surface through the water (see Figure 90).

As the collector temperature is further increased, the rate of heat transfer also rises and the vapor bubbles increase until the heat transfer (power density) reaches a peak of 870 watts/inches^2 (similar to the example of Figure 91). This is the maximum point of safe heat transfer.

If the collector temperature or power density is increased above 125°C (870 W/in^2), the maximum limit, the heat transfer decreases as shown in the graph. The surface of the collector becomes partially insulated by the vapor and prevents the liquid from rising to the surface to evaporate. This region is called

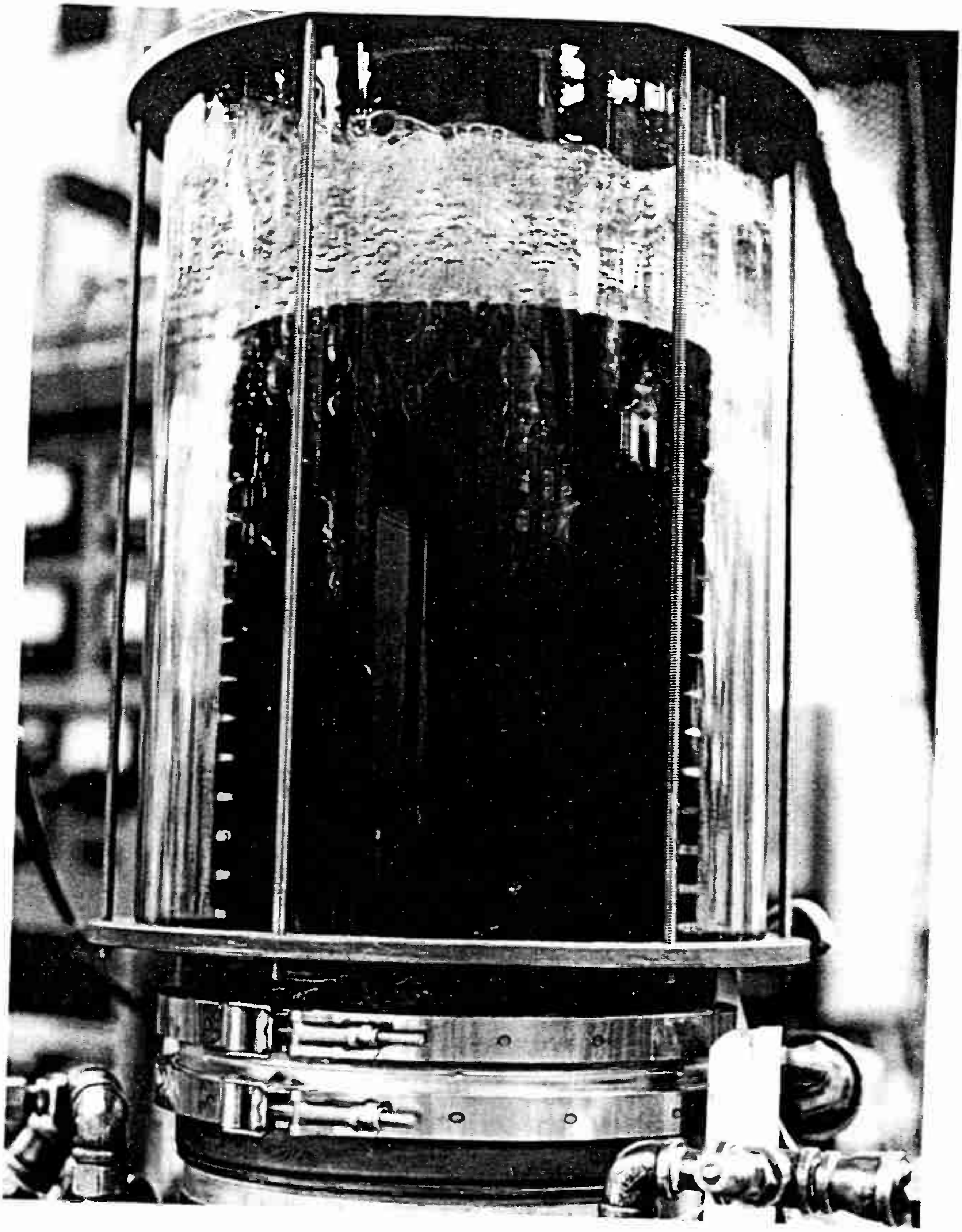


FIGURE 90: VAPOR COOLED COLLECTOR UNDER TEST WITH TRANSPARENT BOILER HOUSING
Photo courtesy of Varian Associates Inc.

FIGURE 91: VAPOR COOLED COLLECTOR UNDER TEST WITH TRANSPARENT BOILER HOUSING. HIGH BOILING RATE
Photo courtesy of Varian Associates Inc.

partial film boiling or an area of unstable boiling (B to C on Figure 89).

An increase in temperature could be caused by:

1. An increase in beam power to the klystron beyond the maximum limit of operation
2. A reduction in coolant flow to the collector
3. Too much back pressure in the output vapor line causing a reduction in the height of the coolant covering the collector
4. Excessive copper scaling on the collector surface preventing the collector from transferring heat efficiently.

This effect gets worse as shown in the graph of Figure 89. The heat transfer capability drops until the collector temperature reaches 225°C. At this temperature the collector becomes completely insulated by vapor; this is the beginning of the film boiling region (C to D on Figure 89).

If the collector temperature continues to rise above 225°C, the heat transfer capability begins to increase again, but does not reach the 870 W/in^2 power density until the temperature is 1000°C. This is a very dangerous condition for the tube as the heat transfer versus collector surface temperature curve in Figure 89 is irreversible under certain conditions.

This irreversible condition is based on a surface more or less large and capable of transferring the heat under normal conditions but is isothermal (all points of the large surface reach the critical operation region simultaneously). Under these conditions, when the thermal exchange suddenly rises from below B to D on the graph, the collector would most likely be destroyed.

A damaged or destroyed collector might appear similar to those in Figures 89 and 92. It is not implied that these damaged collectors were isothermal. They are merely examples of damaged collectors.

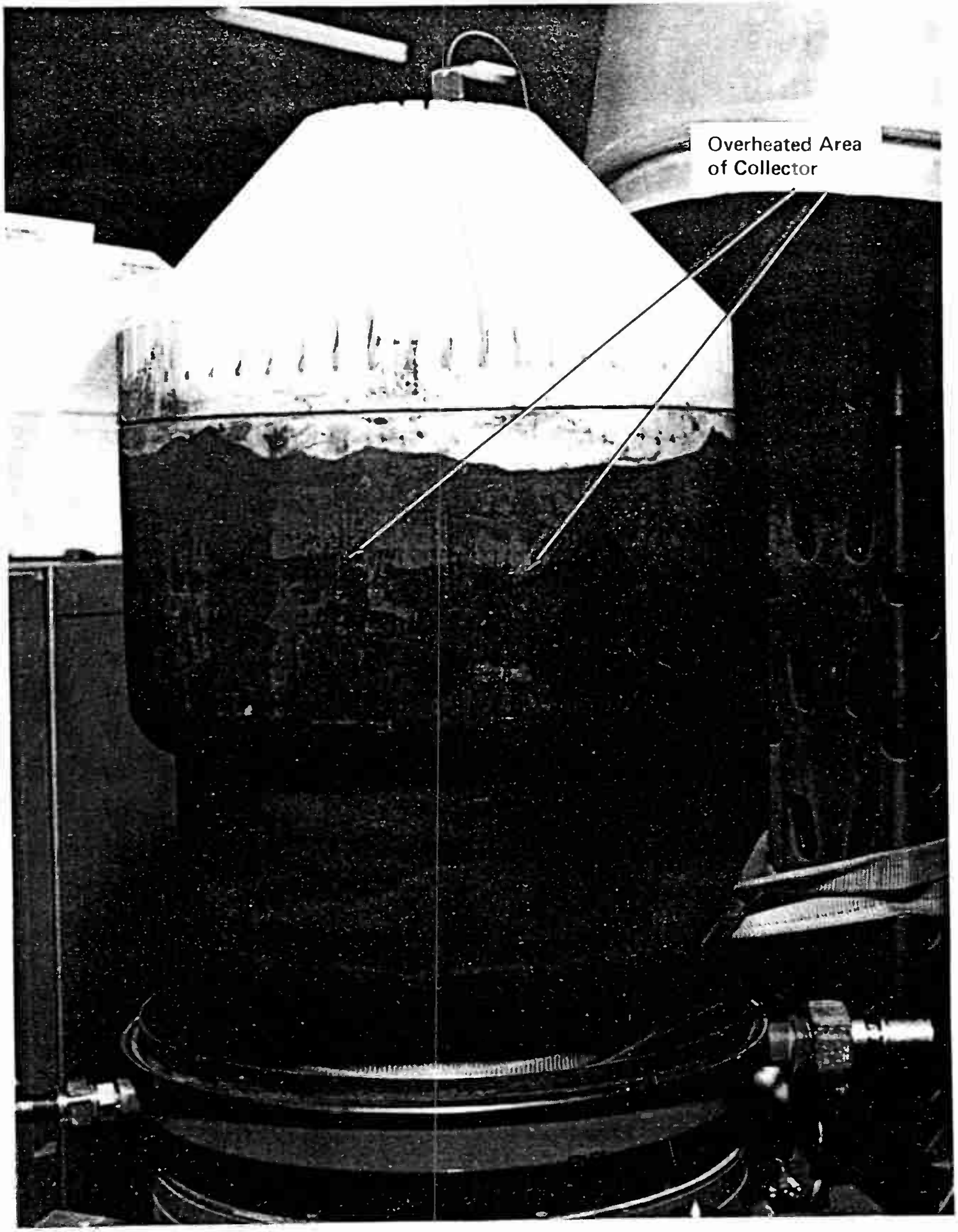


FIGURE 92: EXTERNAL VIEW OF OVERHEATED VAPOR COOLED COLLECTOR
Photo courtesy of Varian Associates Inc.

Since collector configuration is one of the important design considerations, the curve of Figure 89 (ABCE) can be run in a reversible and stable fashion at all points if, and only if, the following requirements are met

1. The length of the radial extensions or the ends of the protrusions must be constantly wetted by the cooling liquid.
2. The thickness of the metal or protrusions of the collector must be such that the conductibility of the underlying metal ensures the spreading of the temperature without discontinuity along the lateral surface of the protrusions.

Although there may be different collector design considerations for power capability or efficiency between manufacturers, the standard surface configuration of most vapor cooled collectors that are now in use, and in particular UHF-TV klystrons, meet these requirements.

Early research by C. Beurthert[8] shows that because of the peculiar structure of a vapor cooled collector, the surface in contact with the cooling liquid presents a non-uniform temperature distribution. The temperature also varies from the bottom to the top of a klystron collector, partly due to beam dispersion inside of the collector. The temperature also varies along the length of the protrusions or grooves. These facts, along with a massive collector and protrusions, ensures a transverse thermal link between the surface elements.

Under normal operation, the ends of the protrusions or outer surface do not participate in the boiling process. The external metal surface, constantly in contact with the boiling water in motion, has a temperature slightly higher than 100°C. For a given operating condition or dissipation, the temperature varies progressively along the protrusions to the bottom of the grooves, which in turn, will vary with the dissipation rate.

The thermal conductibility presented by the thickness of the underlying metal is incompatible with a large temperature difference such as 900°C between two neighboring points on the surface. The physical impossibility of going from points B to D on the graph under these conditions constrains the representative point to go through all the successive points on the curve BCD. The zone (BC) of unstable operation is thus stabilized continuity between the two operating zones of stable operation AB and CD. The curve ABCE can thus be run in a reversible and stable fashion at all points.

Of course there is a limit as to how long a given collector can be operated at a temperature or power density above the designed level. Thermal sensors must be in good working condition in order to sense an increase so that there is no possibility of destroying the collector. Even with this apparent disadvantage of collector damage when the maximum power density is exceeded, the vapor cooled collector in comparison to the forced liquid cooled collector is not difficult to operate and does have a much greater heat-transfer capability.

6.4 Collector Operation

The coolant flow and thermal parameters of the two previously described collectors, forced-liquid-cooled and vapor-cooled, are obviously different in construction and operation. Disregarding the system manufacture's differences in the wiring and external metering circuit, the electrical operation of both collectors is basically the same.

As the electron beam travels through the rf circuits of a klystron amplifier, it is confined by a strong magnetic field. However, some of the energy is intercepted by parts of the rf structure, registering as body current. A substantial amount of energy is also transferred to the output cavity, to the coupling loop and then to an external load or antenna. The remaining energy in the electron beam is attracted to the positive potential of the collector and collides with the inside wall with a certain amount of energy and is then transformed into thermal energy which heats the collector wall. The heat is then transferred to the surrounding coolant which is in liquid contact with the outer collector surface.

The magnetic field which has focused the beam through the rf section of the klystron is rapidly reduced to zero beyond the output cavity (Refer to Section 4.0 on Magnets). Therefore, the collector is substantially a field-free region, and the electron beam, on leaving the magnetic field, will expand because of it's own space charge forces and will strike the inner collector wall. Most of the electrons strike the collector wall in a band near its open end, gradually decreasing towards the upper part of the collector. Thus the distribution of heat is non-uniform along the length of the collector, being maximum in the region near the open end. If the beam was not allowed to expand but continue as a confined beam, it would burn a hole through the upper part of the collector, destroying the tube.

Another feature of most collectors is a plate attached to the collector entrance with an opening that is smaller than the inside diameter of the collector. It is sometimes referred to as a fly-trap. This prevents or reduces secondary electrons that may return from the collector and travel back down the drift tubes, reducing the efficiency of the tube. Refer to Figures 83, 84, 87 and 88 for illustrations of the fly-trap.

There have been recent developments in high-efficiency tubes and collectors, trying to reduce secondary electrons. In particular, many of the internal cavity UHF-TV tubes now use what is commonly called a high-efficiency collector similar to the illustration of Figure 93 and the previous burned collector shown in Figure 92. On the average, there is a 5 to 10 percent improvement in the overall tube efficiency with this type collector on UHF-TV klystrons.

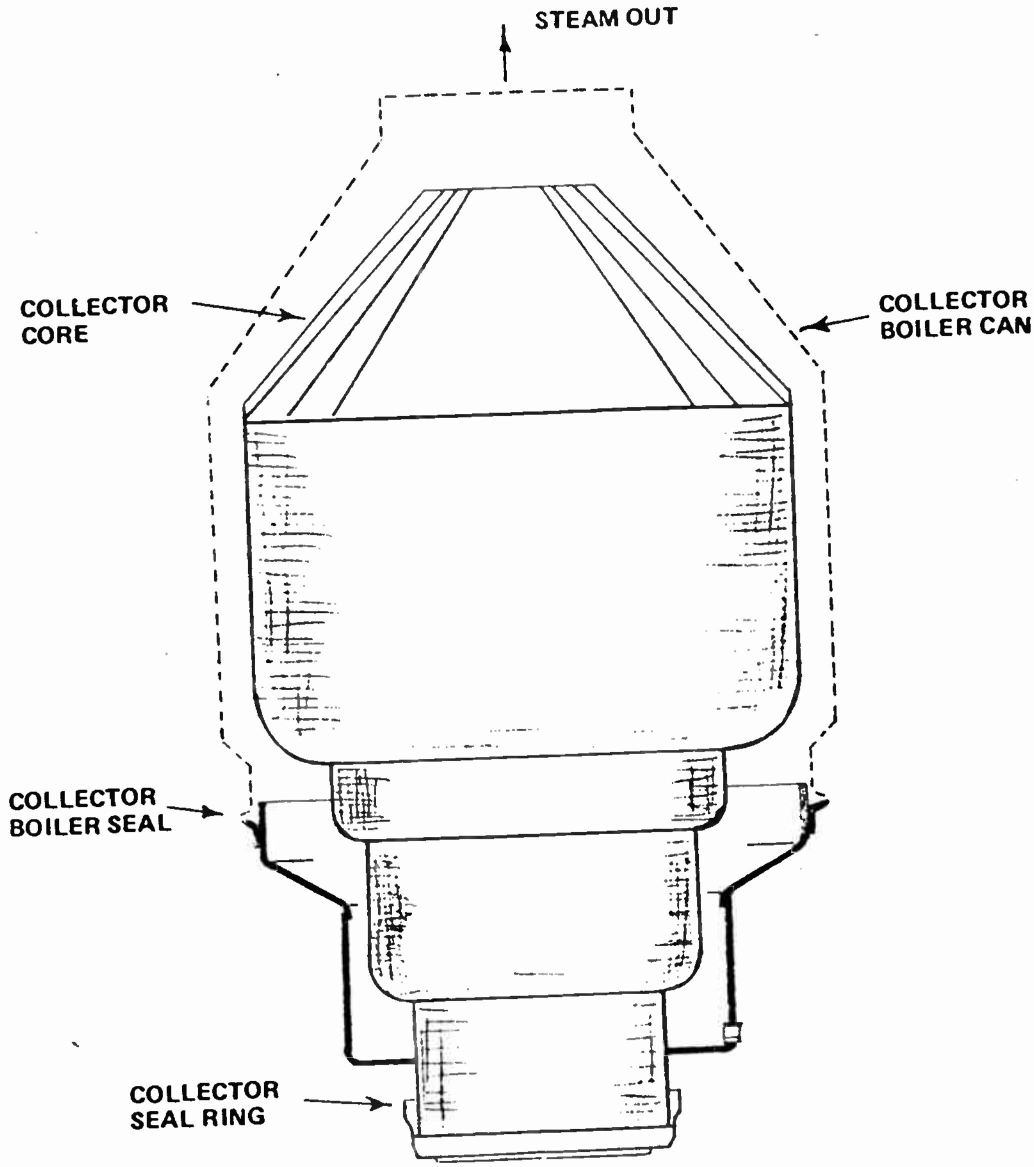


FIGURE 93 : TYPICAL HIGH EFFICIENCY VAPOR COOLED COLLECTOR

As discussed earlier in Section 4.0 on magnets, the magnetic field shape is controlled in part by the geometrical shape and size of the material used in the magnet pole piece and the upper and lower pole pieces that seat the tube to the magnet. As an example, if a klystron had a very long collector for one reason or another, the magnetic field might not be reduced immediately at the collector end, but would be reduced more gradually so that the beam was distributed over a longer area.

The axial current distribution in the rf section and the collector, and hence heat distribution, also varies depending on the level of the rf output power from the tube. Most high-powered klystrons have collectors that are insulated from the rf section to permit separate metering of the electrons intercepted by the drift tubes and those intercepted by the collector. The electrons intercepted by the drift tubes is normally referred to as body current, while those intercepted by the collector are referred to as collector current. The sum of the body current and collector current equal the total current in the electron beam.

In most systems, the collector and body operate at nearly the same potential; normally, the only difference is in voltage drop across the various metering circuits. The most frequent method of operation is with the klystron body grounded. Figure 94 illustrates a typical basic circuit used to monitor the body current, collector current and total beam current separately, with arrows indicating the direction of electron current flow.

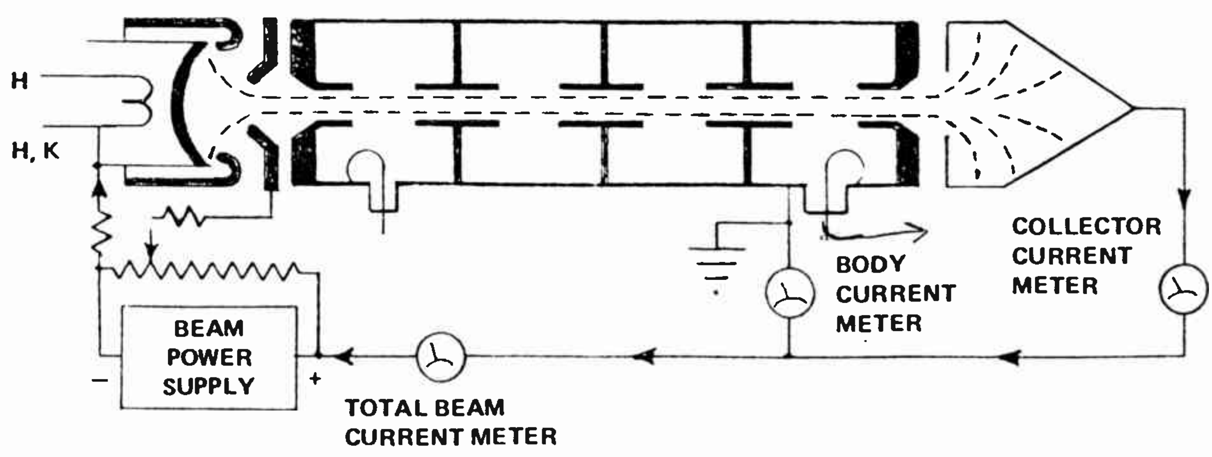


FIGURE 94 : BASIC KLYSTRON METERING FOR COLLECTOR, BODY AND BEAM CURRENTS SHOWING ELECTRON CURRENT FLOW

Three meters form a network that connects the body and collector of the klystron to the positive terminal of the beam supply that is normally operated at ground for safety reasons. The resistor across the beam power supply forms a resistive divider which can provide the necessary bias voltage for the modulating anode. The resistor connected to the modulating anode is in series with any current that may flow between the modulating anode and the power supply. The resistor in the negative lead connected to the cathode limits the current through the klystron so an arc anywhere in the high voltage will not damage the tube.

7.0 PERVEANCE

7.1 Perveance

You won't find the word perveance in a standard dictionary, but it is an often used word in the Microwave Tube Industry. It is seldom used or brought up in conversation with the end user when discussing klystrons or other similar microwave tubes. However, an understanding of perveance will help to interpret the earlier discussion on electron guns.

Perveance was first mentioned in Sections 3.5 and 5.5.2. It is a numerical constant which relates the magnitude of the current to the beam voltage in a diode which consists of an anode and cathode. It also assumes the device to be a vacuum diode. It is, in part, a function of the cathode-to-anode spacing, although it does not depend on absolute spacing.

For example, if we had two planes of unit area separated by some distance "X," one an emitter or cathode and one an anode, the electrons which move from the cathode to the anode will be a function of the voltage between the cathode and anode. When the emitter is being operated so the electrons moving from the emitter are limited by the space charge (i.e. the electron cloud between the cathode and anode) and not the emission capability of the cathode, the relationship is:

$$I = K(E)^{3/2} \quad \text{or} \quad K = \frac{I}{E\sqrt{E}}$$

where K = Perveance

I = Beam current in amperes

E = Beam voltage in volts.

Under these conditions it is evident that if the cathode and anode area were increased by a factor of two, the current would increase by a factor of two. Therefore, the constant for any diode is proportional to the area of the cathode and anode. On the other hand, if the spacing between the cathode and the anode is changed, the current would also change. If the spacing were reduced by a distance one half of the original spacing, the current would increase by 2.82 times the original current. The latter follows because the "E" in the above equation is really a voltage gradient or the voltage between the cathode and anode divided by the distance. If the original spacing were 1.0 units and the voltage were 100 volts, the gradient would be 100 volts/unit length. If the spacing were reduced by a factor of two the gradient would be 200 volts/unit length and therefore;

$$\left(\frac{200}{100}\right)^{3/2} = 2.82:1$$

The perveance of a completed electron gun in a klystron is dependent on the spacings affecting the area and distance in the manner described, except that the geometry is more complex than in the simple diode. The use of microperveance (or μperv) is the result of units. If we are using volts and amperes and have a gun whose microperveance is 1.0×10^{-6} the following would result. At 10,000 volts the cathode current would be 1.0 amperes.

$$1.0 = K(10,000)^{3/2}$$

$$1.0 = K\ 1.0 \times 10^{-6}$$

or

$$K = 1.0 \times 10^{-6}$$

The perveance set by the manufacturer is a part of the electron gun design and remains constant. It is usually determined by the overall klystron design and operating parameters of the tube.

The basic electron gun, as described earlier in Section 2.2 and called cathode control, has no means of changing perveance by the end user. The mod-anode control electron guns also have a fixed electron gun perveance; however, by changing the mod-anode voltage which affects the beam current, the beam perveance can be changed. Do not confuse gun perveance with beam perveance, there is a difference which will be explained later in this section.

Most of the factors that affect the operation of a klystron amplifier, except perveance, have been discussed in detail in the preceding sections. However, because the cathode operation is an important factor in the overall klystron operation, consideration shall be given in this section not only to perveance characteristics but also to other relevant areas such as cathode operating temperature and how the perveance relates to the bandwidth of a klystron.

7.2 Beam Current, Cathode Temperature Characteristics

All cathodes, regardless of the type of emitting material used, are designed for operation within definite temperature limits to assure maximum operating life and efficiency. In addition, the operating temperature of the cathode must be at such a value that variations in the heater power will not affect the electron emission current in the klystron. The temperature of the emitting surface must not be higher than necessary since excessive temperature will cause deterioration of the emitter, shortening the life of the cathode.

It is obvious that one cannot measure the temperature of a cathode on a completed tube, this can be done only in the laboratory during the initial fabrication of the electron gun. However, the heater voltage (or heater power) can be related to the temperature by plotting a curve of beam current vs heater voltage at various beam voltage levels. In order to plot beam current vs related temperature data on a completed klystron, variable power supplies are needed for the heater voltage and beam voltage. This would appear to be a problem in some cases, since most commercially available transmitter systems, whether they are for communications or UHF-TV transmitters, do not have continuously variable power supplies, only various tapped voltage levels. In any case, this is not a real problem: even with tapped voltage levels the measurements can be made, but with some reduced accuracy. The important object here is the understanding of the concept as it will benefit the end user.

> NOTE: These measurements would normally be performed only on a tube that has exhibited a deterioration of beam current, as the correct operating level is chosen by the manufacture of the klystron when it is initially tested. It has also been stated previously in Sections 3.1 and 3.2.2,

NOTE: (continued)

that before conducting a test such as this, the tube manufacturer should be consulted for recommendations before proceeding.

Let us assume now that there are means for adjusting the power supply voltages and for this example the beam voltage is 18 kVdc. At this point it should be mentioned that if this type of test is conducted on a tube with a basic cathode-control electron gun (no mod-anode), the 18 kVdc would be the only high voltage to be concerned with. Since the main concern here is with UHF-TV klystrons or any tube that has a modulating anode, there is a mod-anode voltage to be aware of, so the voltage will be 17 kVdc (E_1) for this part of the example. A typical block diagram and circuit for the tube and power supplies is shown in Figure 95.

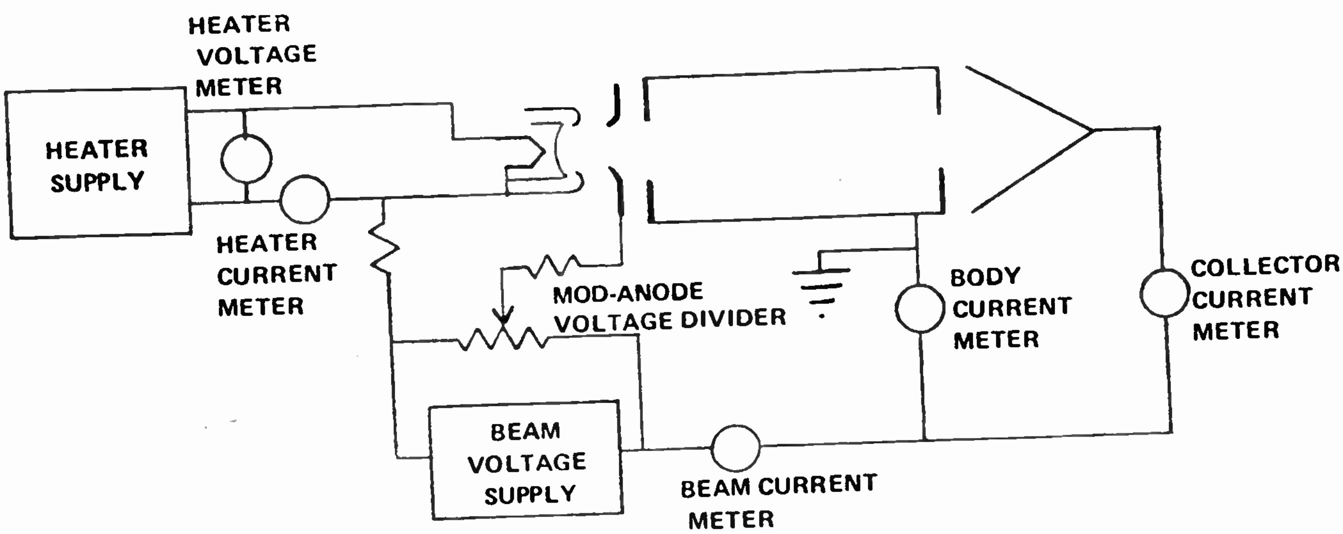


FIGURE 95 : KLYSTRON POWER SUPPLY AND METERING

From these high-voltage levels a beam current vs heater voltage plot can be made as shown in the example of Figure 96 which is typical of most klystrons. The curves are made by maintaining a fixed mod-anode voltage (E_1) and a fixed beam voltage of 18 kVdc, then varying the heater voltage over some range in order to establish a profile of the beam current.

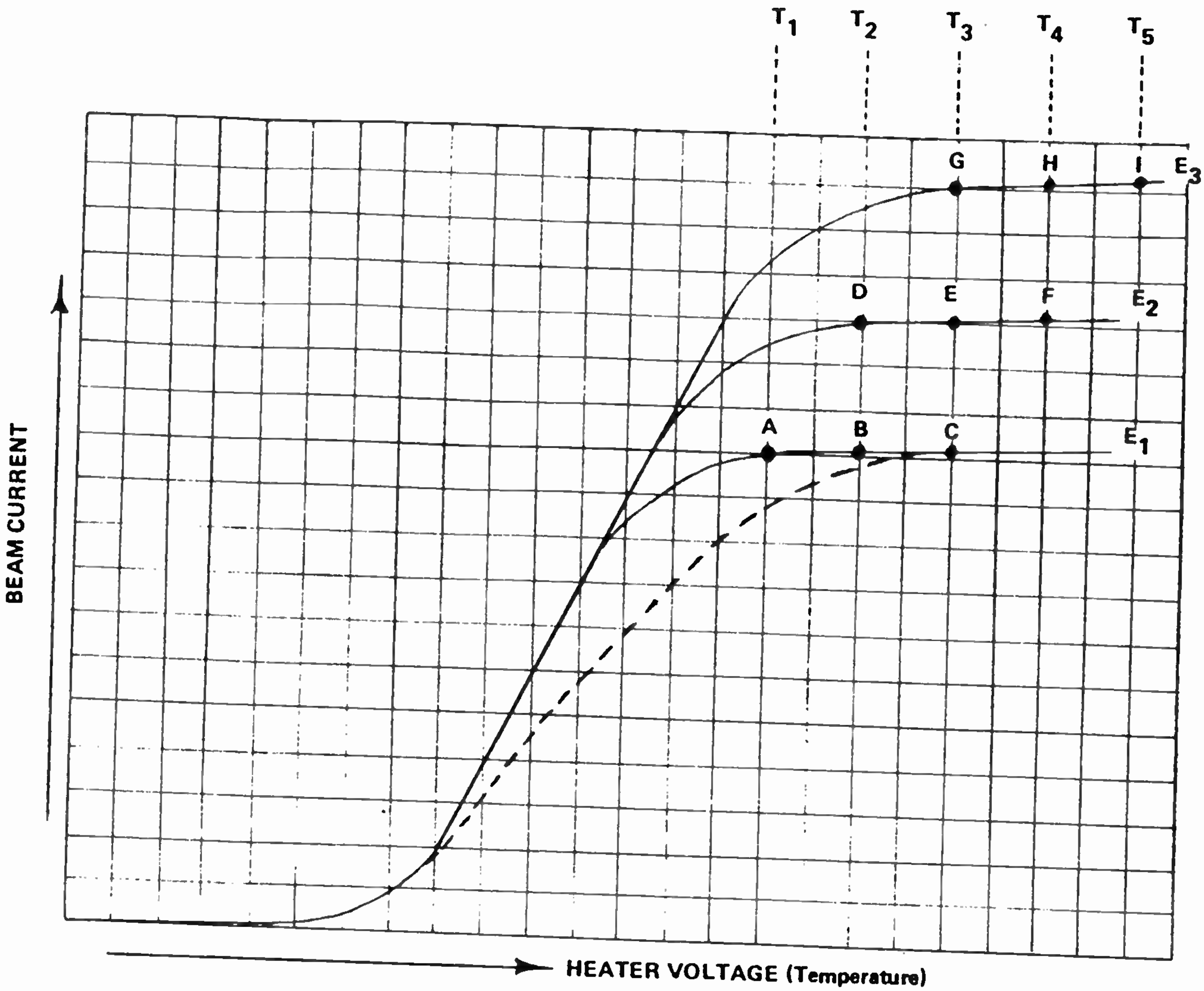


FIGURE 96 : BEAM CURRENT vs HEATER VOLTAGE (Temperature) CHARACTERISTICS AT THREE HIGH VOLTAGE LEVELS

These curves are what you would expect from a new tube, or one that has not deteriorated in beam current. The operating temperatures are between T_1 and T_5. Below these values of "T" at the knee of the curves the current falls rapidly and above the values of "T" at the knee, the current remains substantially constant. The mod-anode operating voltages are labeled as E_1 to E_3.

With the mod-anode and beam voltages set as stated above, and the heater voltage set at zero, the resultant beam current is zero. As the heater voltage is slowly increased, and held at each level to stabilize, the temperature of the emitter will rise. At first there will be no indication of beam current, then as the emitting surface of the cathode reaches some higher temperature, the beam current will start to flow. The beam current will continue to increase for each rise in the heater voltage until eventually it will flatten when the emission saturation point (A of Figure 96) is reached on curve E_1.

Point A on curve E_1 also corresponds to an emitter temperature T_1. Increasing the temperature beyond this value of heater voltage to T_2 or T_3 will not increase the beam current significantly for the particular high voltage setting. Beyond the heater voltage for temperature T_1, the increased emission contributes little to the beam current since the number of electrons pulled out of the space charge by the high voltage is not increased, only the density of the space charge is increased. In other words, the beam current has reached an area of temperature saturation, so the operating point for voltage E_1 would be between T_1 and T_2.

Other operating ranges are also shown in Figure 96 labeled E_2 and E_3 and indicating other temperature ranges of emitter operation. Originally a beam voltage of 18 kVdc was chosen along with a mod-anode voltage of 17 kVdc. Let us now raise the mod-anode voltage to 17.5 kVdc (E_2) while the beam voltage remains at 18 kVdc. The emission saturation point for this level is now point "D," corresponding to temperature T_2. In the last curve (E_3), again the beam voltage remains at 18 kVdc and the mod-anode voltage also is set at 18 kVdc. The emission saturation point for this level is now "G," corresponding to temperature T_3. This indicates that for every different operating condition (E_1, E_2, E_3), there is also a different range of temperatures. So the operating point for E_2 would be between T_2 and T_3, and for E_3 it would be between T_3 and T_4. For a margin of safety due to possible variations in heater voltage, the operating points for any of the curves shown should be above the knee of the curves. In a like manner, if both the beam voltage and mod-anode voltage were varied, there would be a similar curve but a different set of results.

The total operating temperature ranges for the high voltages indicated or any practical voltage range for a given tube type could be stated as extending from T_1 to above T_4. However, the operating range for any given beam voltage and/or mod-anode voltage would be much smaller than the total range, such as the range of E_3 from T_3 to slightly above the temperature of T_4. In addition, any cathode (emitter) that is operating at temperature T_1 will not be functioning along the temperature saturation area of the curve if the voltage were raised from E_1 to E_2 or E_3. However, a cathode that is operating at temperature T_3 or T_4 would still be in the temperature saturation part of the curve if the voltage were lowered from E_3 to E_1. This then indicates that it is permissible to operate a klystron with high voltages that are lower than specified, but there is a limit as to how far above specified values it would be safe to operate.

> NOTE: Before operating any klystron outside of the specified limits supplied to the end user, the manufacturer should be consulted for recommendations.

There are alternate methods of performing the measurements of beam current vs heater voltage profile, such as varying both the beam voltage and mod-anode voltage, setting them at specific levels and varying the heater voltage to establish a curve. However, when choosing voltages for the mod-anode and cathode, such as a lower mod-anode voltage, the same percentage difference should be maintained when raising or lowering the high voltages to some set level.

Another important aspect in cathode operation is the behavior of cathode emission characteristics during the life of the tube. The emission will decline over a period of time; after hundreds of hours of operation or in a shorter time due to a tube/system failure, which also damages the cathode. The knee of the curve generally moves to the right of the curve (dash line in Figure 96). Operation of the tube can usually be compensated for by raising the heater voltage enough to put the cathode back in the emission saturation region and/or a combination of raising the heater voltage and the mod-anode voltage or beam voltage to achieve the desired beam current or power output.

Of course, this can only be done if there is available emitting material in the cathode and if the tube failure was not serious enough to destroy the entire emitting surface.

The actual change in heater voltage needed to establish a new emission point on a decayed cathode will vary from tube type to tube type; it may be as small as 0.5 volts or as large as 2.0 volts to change from T_1 to T_3 and above. The measurements of heater voltage will also depend in part on the available controls within any given transmitter system. For all practical purposes, the most important part of the curves of Figure 96 is establishing the emission saturation point and the knee of the curves where the beam current rolls off.

7.3 Operational Voltage and Perveance

Another meaningful presentation of klystron operation is the perveance graph, plotting beam current vs beam voltage or mod-anode voltage on two thirds power graph paper. Figure 97 is a simplified illustration showing how the beam current changes, following a straight line when various beam/mod-anode voltages are applied and while the heater power or emitter temperature is held constant at different levels. The values of E_1, E_2, E_3 and T_1, T_2 and T_3 depict the relationship to the emission saturation curves shown earlier.

The three straight lines are labeled K_1, K_2 and K_3 which is the symbol for perveance and the plotted beam current vs beam/mod-anode voltage follow one of these straight lines. The electron gun perveance cannot change, it remains constant throughout the life of the tube, but there are certain parameters that will appear to affect it.

Most tubes are designed for some given fixed gun perveance, and for any given tube type there is usually a tolerance for the maximum and minimum perveance the tube is allowed for operation within its operating parameters. This is indicated by the K_1, K_2 and K_3 lines. In this example, we shall say the tube is operating with an electron gun perveance of K_1 (the minimum design value), and it is along this line that the emission from the cathode is considered to be space-charge limited. In other words, space-charge limited (see Section 3.4) means that the voltage fields

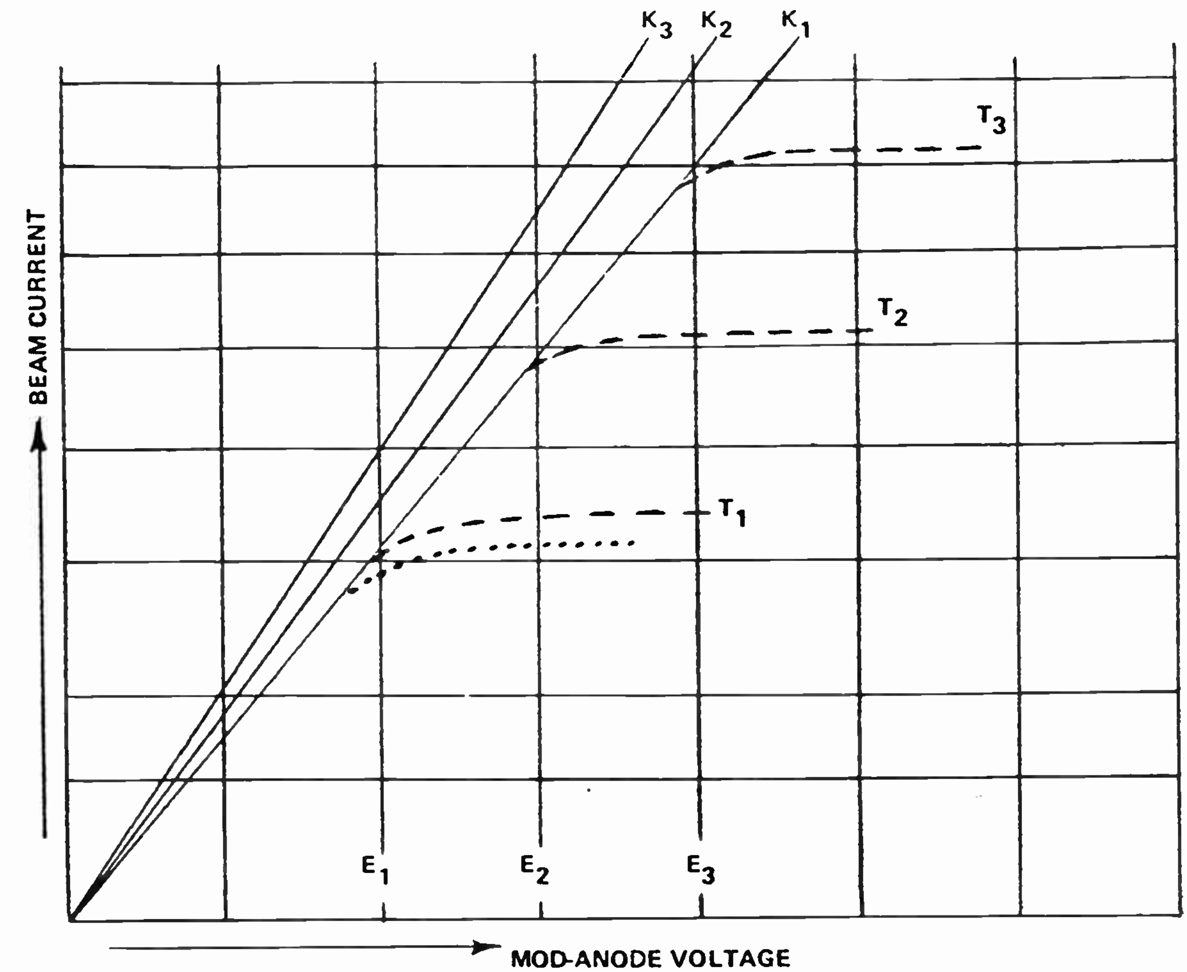


FIGURE 97 : PERVEANCE

in the area of the cathode and anode control the amount of current that is being drawn to the anode of the klystron. By using semilog graph paper to plot the two-thirds power of the beam current as a function of beam voltage (or mod-anode voltage), the perveance becomes a straight line, and the beam current for any given value of high voltage can be obtained.

As mentioned before, if there is only one high voltage source to be concerned with (e.g., cathode voltage), this would be the only high voltage to vary. However, let us again use the same voltages stated previously for the examples of temperature saturation. The beam voltage will be fixed at 18 kVdc and the values of E_1, E_2 and

E_3 will again be 17, 17.5 and 18 kVdc respectively. Heater voltage operation will also be referenced to T_1, T_2 and T_3, and the diagram of Figure 95 will be the basis for measurements.

If the heater power were set for a relative emitter temperature T_1 and a fixed beam voltage of 18 kVdc were applied, the beam current would be zero if the mod-anode voltage (E_1) were set at zero. As the mod-anode voltage is raised, pausing at some cardinal voltage level below the E_1 value of 17 kVdc, the measured beam current will fall on the K_1 perveance line. For each cardinal point the mod-anode voltage is set to, the beam current will follow the K_1 line.

When the mod-anode voltage reaches the E_1 value of 17 kVdc and the temperature of the emitting surface is at T_1, the cathode will then be operating "temperature limited." Temperature limited means that the beam current is sensitive to changes in temperature and that the current reaching the anode is now being controlled by the number of electrons being thermally driven off of the emitter surface. The temperature limited condition is unstable and klystrons are not designed to operate in this region since the effects are unpredictable. Refer to T_1 and E_1 in Figure 96. The beam current has just reached a stable point at T_1, but if there are any downward fluctuations of the heater voltage, the beam current will tend to roll off the knee of the curve. This is also indicated by the dotted line below the T_1 line in Figure 97. If there is a further increase in the mod-anode voltage above E_1 to E_2 or E_3 with the same heater voltage indicated by T_1, the beam current will tend to flatten out as shown in the graph. The only way to raise the beam current back to its normal operating level on the K_1 line is to increase the emitter temperature.

The plots of Figure 97 are exaggerated to some degree for explanatory purposes, but it should be obvious that the heater voltage (indicated by an emitter temperature T_1) is critical to the operation of a klystron and it is necessary to operate the tube at a temperature where the cathode will be stable.

Let us now examine a more detailed presentation of a perveance plot using some specific values of <u>voltage</u>, <u>current</u> and <u>perveance.</u> Figure 98 is a detailed plot indi-

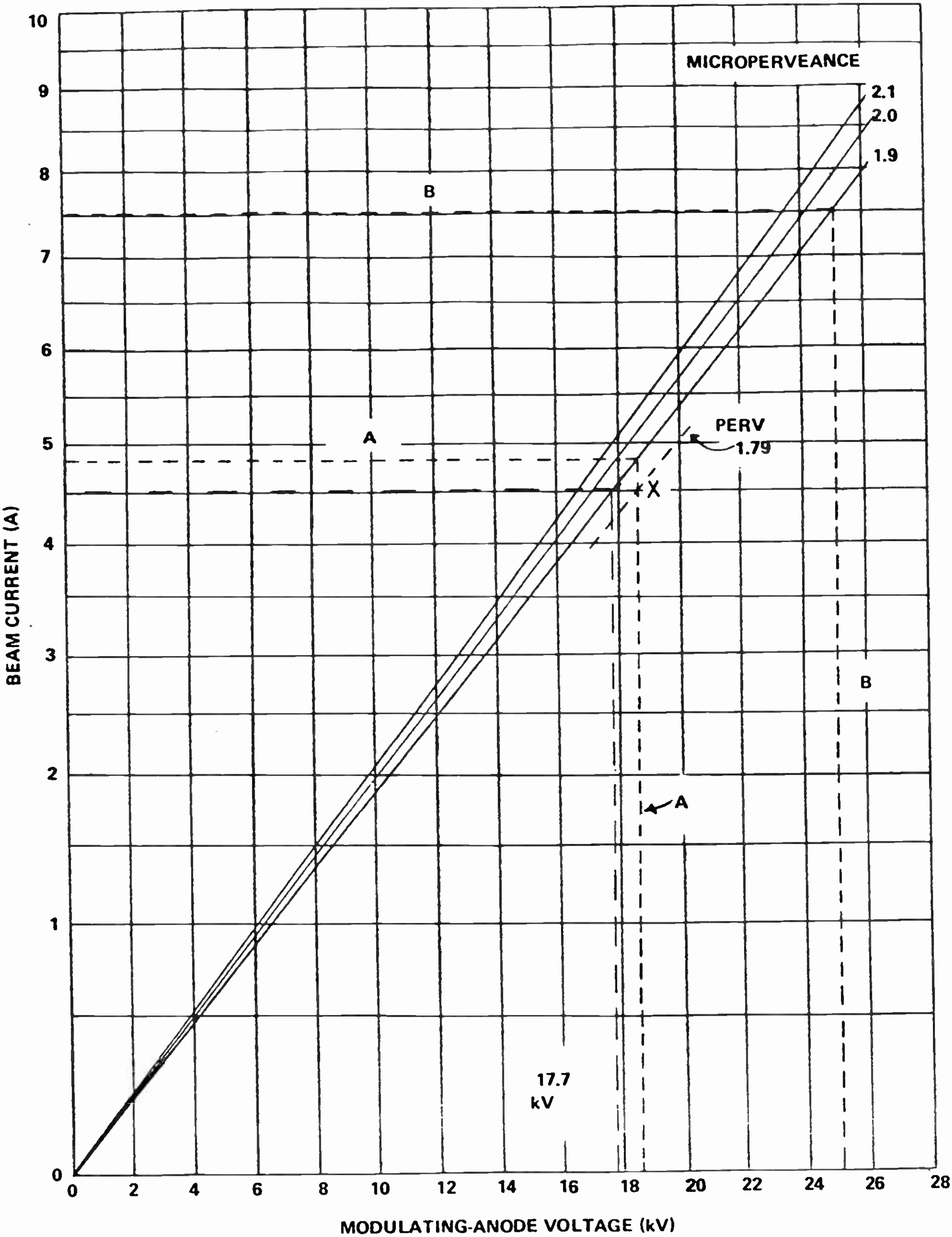


FIGURE 98 : MOD-ANODE VOLTAGE vs BEAM CURRENT FOR MICROPERVEANCE 1.9 TO 2.1

cating a 1.9, 2.0 and 2.0 gun perveance. Typically UHF-TV klystrons are built with an electron gun perveance between 1.9 and 2.1. This graph can be used to determine any of the above parameters, given the other two, for klystrons operating in the perveance range of 1.9 to 2.1.

For example, assume now that the correct operating heater voltage has been applied so that the cathode is stable. Let the klystron beam voltage and mod-anode voltage both be 18.5 kVdc and the beam current is 4.78 amps. These points are marked "A" on the graph which fall on the 1.9 perveance line. Similarly, a tube operating at 25 kVdc for both the beam voltage and mod-anode voltage, would have a beam current of 7.51 amps. These points are marked "B" on the graph which fall on the 1.9 perveance line also.

If we now set 18.5 kVdc beam voltage on a given tube and adjust the mod-anode voltage for a beam current of 4.51 amps, the mod-anode voltage would be ≅ 17.7 kVdc which would intersect on the 1.9 perveance line. What is also indicated here but usually ignored is that while the gun perveance remains constant at 1.9, the beam perveance has been lowered to 1.79 because the beam voltage is still at 18.5 kVdc (indicated by the "X" on the dotted line of the graph). The importance of perveance and especially in this case where the beam perveance is lower than the gun perveance, is in its influence on the operating bandwidth of the klystron. Multi-cavity klystrons that are adjusted for high efficiency and bandwidth depend primarily on the loaded Q of the output cavity, the earlier input and intermediate cavities being capable of being adequately loaded to achieve a broader bandwidth. Certainly there are other factors that effect the overall operation and bandwidth of a klystron, such as the number of cavities and cavity gap spacing etc, but in this case they can be ignored.

This loading is also in part a function of the beam current that the output cavity see' s passing through it, commonly called beam loading. Less current decreases the load and increases the Q, thus decreasing the electronic tuning or bandwidth. It can then be stated that the output loaded Q-factor with the load adjusted for optimum efficiency is given by the following equation:

$$Q_L = M\left(\frac{Q}{R}\right)\left(\frac{E}{I}\right) \tag{4}$$

where:

(R/Q) is a geometrical quality factor of the cavity and M is a constant. If we then expressed E and I in terms of beam perveance K and DC beam power, P, (P = EI), the bandwidth Δf which is proportional to $1/Q_L$, may be written;

$$\Delta f = N \left(\frac{R}{Q}\right) K^{4/5} \quad P^{1/5} \qquad (5)$$

where:

N is another constant. Thus, at a given beam power and cavity (R/Q), the bandwidth is almost proportional to perveance.

There is no need to be overly concerned with a reasonable drop in beam current, if you are still able to maintain adequate power input. The reduction in perveance and the two equations (4) and (5) were pointed out to show there is an effect on bandwidth. Most UHF-TV klystrons have more than adequate bandwidth-built into them for operation at all reasonable power inputs.

8.0 KLYSTRON OPERATING CHARACTERISTICS

8.1 Introduction

We will now apply our knowledge of the basic principles of klystron theory to the actual operating characteristics. In this section, we will repeat some previous explanations in order to lay some groundwork for the discussion of certain operating parameters and of course, to reinforce what we have presented.

As we have learned, the power output of a klystron is sensitive to changes in beam/mod-anode voltage, beam current, frequency, drive power, magnetic field strength and tuning. Any variation of these and other parameters will affect the rf output response characteristics. However, klystrons are reliable and stable when properly set up and can be operated at any power level from zero to rated power by changing the rf drive, the beam/mod-anode voltage or both.

All klystrons have the same inherent features, such as gain compression, phase shift and harmonics. The only differences between tube types are the absolute values of the specific characteristics and the mode of operation of the klystron. This section will deal with certain features that are general to all klystron operating characteristics plus specific areas that are related to video operation. It will not deal with any other possible source of distortion of the television signal outside of the immediate interface with the klystron.

8.2 Beam/Mod-Anode Voltage vs Power Output

The klystron, as with any microwave device, is designed to operate efficiently within certain limits. Outside of these limits, the tube will operate, but the designed efficiency or power response will change drastically. In terms of the beam voltage Eb, the perveance K, and the efficiency n (or %), the output power can be described by the following:

$$Po = nKE_b^{5/2} \qquad (1)$$

Generally, the efficiency is also a function of voltage, increasing with higher voltage. The output power is therefore approximately proportional to the voltage cubed. Variations in operating voltage can be used to indicate problem areas. For example, if the beam voltage and/or mod-anode voltage are set below the value specified on the data sheet for a particular klystron, the beam current will be low, and as a result the rf output power response will also be low. Low rf output may also result from a power supply failure or from an incorrect measurement of voltage during the initial set-up. However, if the control anode voltages are set to the correct values specified and the beam current is still low, causing the rf output to be low, it is an indication that the klystron may be at fault. Figure 99 is a typical plot that illustrates how the beam input power affects the rf output of a klystron. The plot shows that for any level of beam input power, there is a maximum amount of power output that can be produced by a klystron.

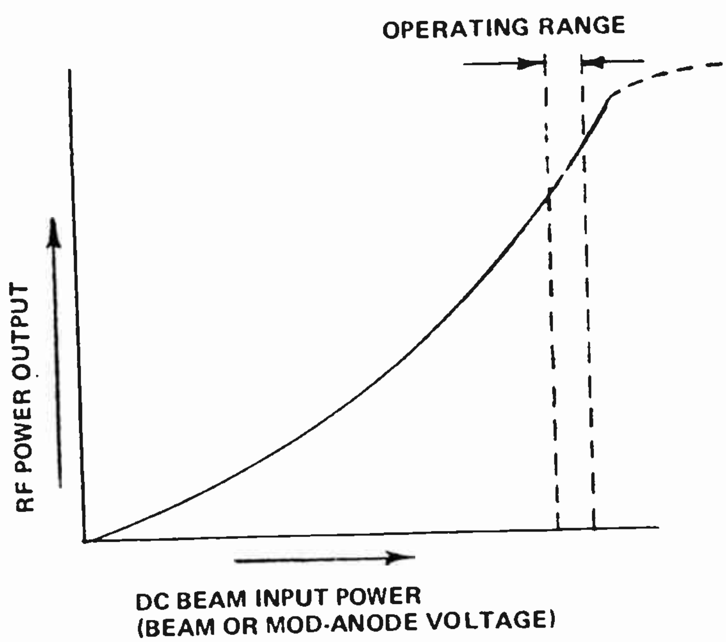


FIGURE 99: POWER OUTPUT VS BEAM INPUT POWER

Small changes in beam input power produce large changes in rf output power, and for this reason, we have two considerations. First, the input power must be great enough to produce sufficient rf output power without sync compression, which is important in TV operation. Secondly, poor regulation will vary the output power, causing phase distortion.

> NOTE: Remember, no voltages or currents may be increased on a tube beyond the maximum ratings or design limits, otherwise the tube may be damaged or destroyed.

8.3 Drive Power vs Power Output

For a given beam power input, the power output of an amplifier klystron is a function of the input rf drive power, depending on the method of tuning. Figure 100 illustrates a typical transfer curve showing the variations of rf power output vs rf drive power at a fixed frequency. The curve also indicates three conditions that exist in the tube's amplification characteristic; small signal, saturation and overdriven.

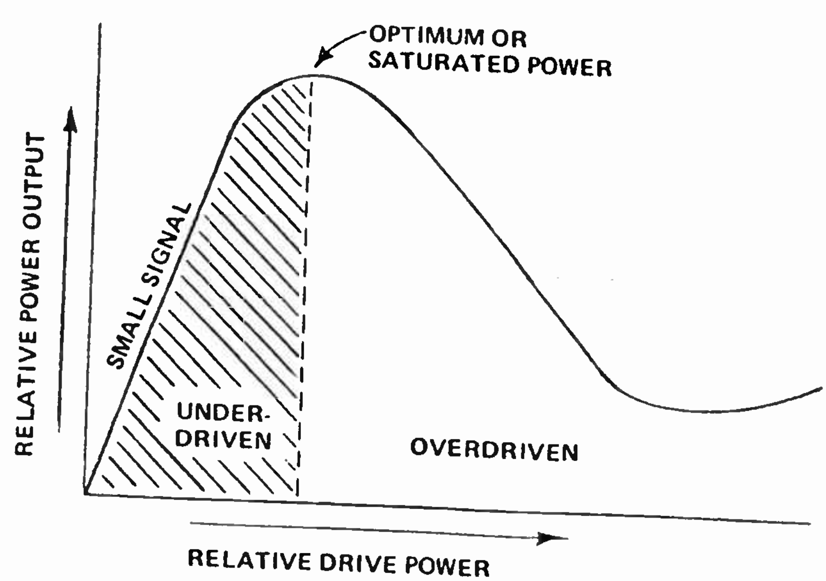


FIGURE 100 : DRIVE POWER VS POWER OUTPUT

NOTE: The term small signal is generally used in reference to tubes that are synchronously tuned; however, these characteristics are much the same for staggered and broadband tuning. This will be covered in more detail as we progress through this section.

The linear portion below the peak of the curve is defined as the small signal region. Here, any doubling of the input rf drive power provides a corresponding increase in rf output power. Thus, for a wide range of input signals, the gain is relatively constant in the small signal region (see Section 5.5.1 and Figure 72). By examining the curve of Figure 100, you can see that as the rf input drive power level is increased, the rf output power increases until an optimum point is reached. The tube is considered drive-saturated at this point due to the electron bunches being most perfectly formed at the instant they reach the output gap of the tube and the beam or bunches are slowed down as energy is extracted from them. This condition exists for all methods of tuning.

A further increase in rf drive power into the area labeled <u>over-driven</u> will only result in a decrease of rf output power and an increase in the amount of beam interception at the drift tubes. All klystrons will exhibit a drop in rf power output beyond saturation, with some more than others exhibiting a large dip and periodic secondary peak with the increasing drive power (refer to Figure 70 also). Klystrons should not be operated in the overdriven region regardless of the mode of tuning.

8.4 <u>Gain and Power Output vs Drive Power</u>

All klystrons characteristically exhibit a curve at the top of the power response as the rf output power approaches saturation. An <u>ideal amplifier</u> would have a constant ratio of rf input and output power until the tube reached saturation as illustrated in Figure 101. In other words, the rf output signal would increase linearly with rf drive until it reached saturation and at this point the maximum possible dc input power would be converted to usable rf output power.

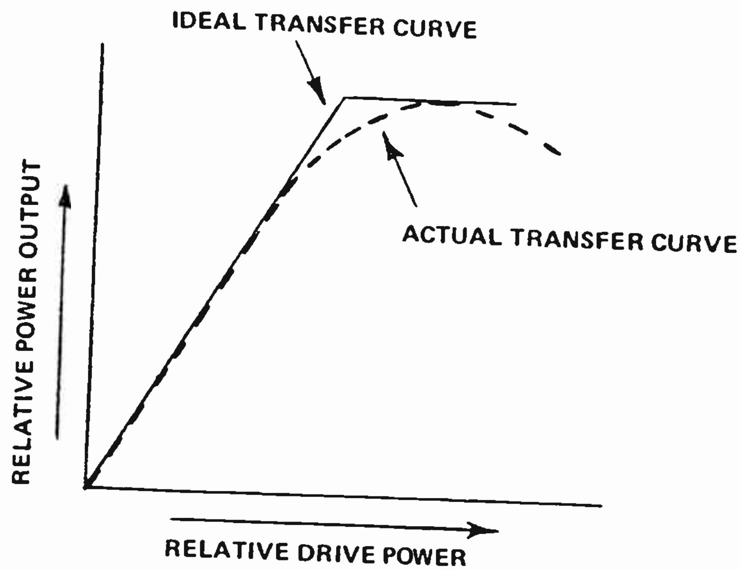


FIGURE 101 : IDEAL VS ACTUAL TRANSFER CURVE OF DRIVE POWER/POWER OUTPUT

As we can see, the klystron is not a perfect linear amplifier and does not follow the ideal curve. However, at lower signal levels, it does follow the ideal curve closely in maintaining a constant gain, but then it becomes non-linear as it approaches saturation. This non-linear condition is illustrated again in Figure 102, which shows that the ratio of output power decreases several dB at saturation. This reduction in gain and non-linear transfer characteristics as saturation is approached, affects the amplification and will modify test waveforms.

The curves in Figure 102 show a typical variation of the rf output power and gain versus rf input drive power at a fixed frequency. The gain is linear in the small signal region and the rf output rises in a linear fashion up to about 70 percent of saturation. Then, as the rf input power is increased beyond that point, the gain reduces and the tube saturates. This phenomenon is called gain compression and is typically a 6 to 7 dB reduction. This may vary slightly according to how the klystron is tuned; i.e., synchronous or broadband tuning.

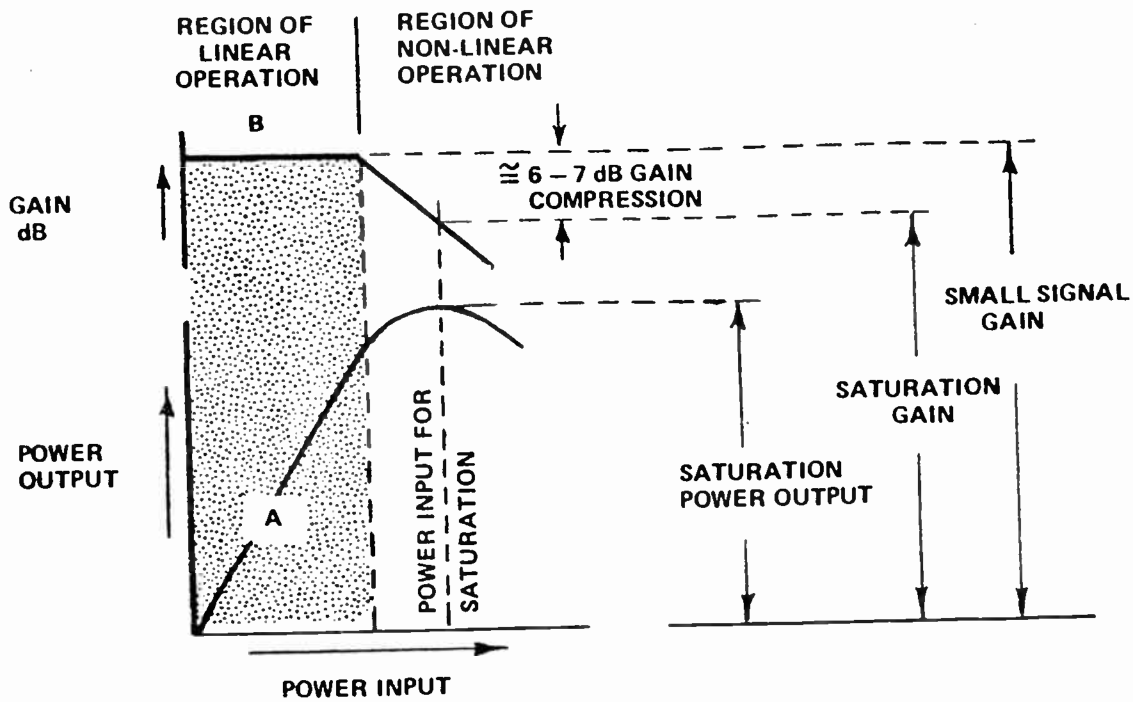


FIGURE 102 : GAIN VS POWER OUTPUT

The gain of a klystron is defined as the ratio of the rf power output to the rf input drive power and is normally expressed in decibels (dB) by the following:

$$G\ dB = 10 \log_{10} \frac{Po}{Pin} \qquad (2)$$

For example, if the input drive power were 8 watts and the output power were 32 kilowatts, the tube would have a power ratio of 4000 which would be equal to approximately 36 dB gain. The above expression of gain holds true for all measurements at all power levels.

8.5 Drive Power and Power Output vs Tuning

In Section 5.5.1, Bunching in Multi-Cavity Klystrons, the different methods of tuning a klystron were briefly described; i.e., synchronous, stagger/efficiency and broadband. It was also pointed out that stagger tuning and broadband tuning were synonymous and often interchanged in conversation when making reference to tuning methods. Efficiency tuning is also a form of stagger tuning but it usually applies to staggering the next to the last cavity (penultimate cavity) for higher power and more efficiency. In this case we will consider the terms stagger tuning and efficiency tuning synonymous. The above methods of tuning are generally described as follows:

1. Synchronous Tuned. Where the frequency of all the cavities in a klystron are peaked for maximum rf output at a single frequency. This method of tuning has the narrowest bandwidth and maximum gain.
2. Stagger or Efficiency Tuned. Where the next to the last cavity (penultimate cavity) is set higher in frequency than the others so there is an increase in the rf output power at a higher drive power than was used before the cavity was tuned. The efficiency is higher and the gain is lower than synchronous tuning. The bandwidth is also a little wider than synchronous tuning, depending on how far the penultimate cavity has been tuned. This tuning is also performed at a single drive frequency.
3. Broadband Tuned. This tuning method will vary according to application and is normally performed with a swept rf drive signal. The number of cavities that make up the klystron will also affect how it is to be tuned. In general usage, the

frequencies of all but the input and output cavities are adjusted so that their center frequencies are staggered on each side of the bandpass of the klystron's center operating frequency and adjusted for a flat top bandpass response. In UHF-TV applications, all but the output cavity are adjusted so their center frequencies are staggered on each side of the bandpass of a center operating frequency and with a flat top on the response. In both cases, the penultimate cavity is always tuned to the high frequency side of the center frequency. The output cavity has a broad response but it is sometimes adjusted a little around center frequency for a final shaping of the flat top on the bandpass. This method offers the widest bandwidth and also requires more rf drive power than synchronous or stagger/efficiency tuning.

Through a series of transfer curves, the different methods can be described to show clearly how the rf power output changes with tuning and rf drive power. The methods that will be described are generally acceptable for all amplifier klystrons; however, there are different modes of operation such as communications, pulse, or UHF-TV which may vary the tuning technique in actual practice. For example, klystrons that are operated as narrow-band communication tubes are generally adjusted to operate at saturation and if they are operated broadband, the bandpass is adjusted so that at saturation there is a flat response. Klystrons used as a video amplifier at UHF are adjusted for a flat bandpass by tuning at mid-grey or blanking, which is well below saturation.

Synchronous tuning and stagger/efficiency tuning are rather straight-forward and can be applied to most all modes of operation, including UHF-TV klystrons that operate as aural tubes. However, no rules can be given to account for all the methods and variations involved in the various broadband tuning techniques. Each system is a separate problem and can only be tuned by careful observance of the instructions which would be supplied by the manufacturer of the klystron or transmitter. Even with specific tuning methods for broadband tuning there are a few basic rules that must be followed, otherwise the tube could be damaged.

Basically, UHF-TV klystrons are all tuned in the same manner but the techniques differ a little from one manufacturer to another. In addition, the internal and external cavity tubes require a little different set-up procedure and adjustments. For example, the alignment of a television receiver is much like tuning klystrons, the basic approach is the same for all TV receivers, but each receiver requires a little different approach to details depending on the manufacturer.

In the next few sections, the basic tuning procedures will be covered along with the output responses that are presented. Coupling and loading will also be covered which is especially important with the external cavity tubes. Specific areas relating to UHF-TV operation will be pointed out where possible but it must be remembered that the procedures covered here are not meant to circumvent any specific manufacturer's procedures.

8.5.1 Synchronous Tuning to Stagger/Efficiency Tuning

Figure 103 represents a series of typical curves of a klystron rf power output at a fixed frequency. Curve "A" represents synchronous tuning and curves "B to F" are the power output responses of the tube as the penultimate cavity is tuned progressively in steps, higher in frequency, adjusting the rf drive for a new saturation point in each case. Typical bandpass examples which are representative of curves A to F are also shown in Figure 104, along with the tuning position of the cavities for both 4 and 5 cavity tubes.

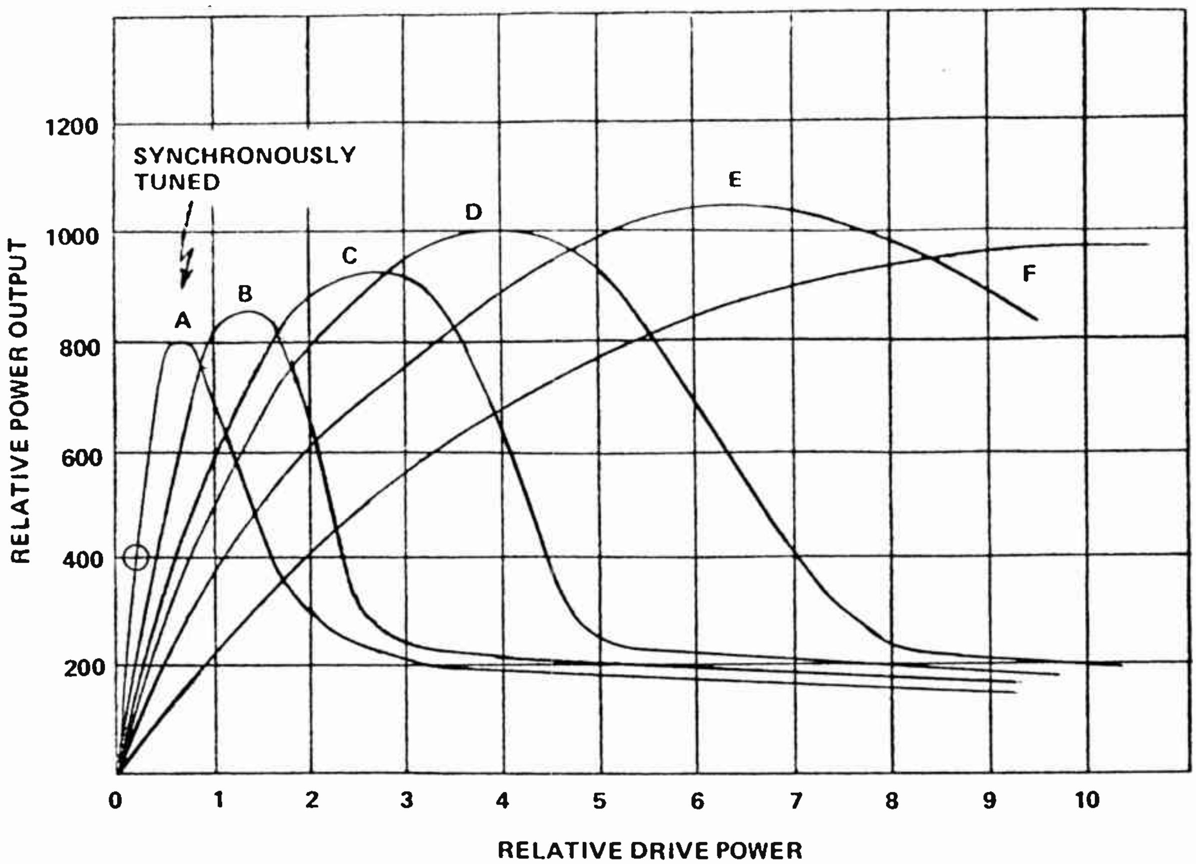


FIGURE 103 : RF POWER OUTPUT VS RF DRIVE POWER AS A RESULT OF PENULTIMATE CAVITY TUNING

Let us now examine how the curves of Figure 103 are created. All tuning is performed with rf only in these examples (no modulation), unless stated otherwise.

NOTE: Some manufacturers of klystrons or transmitters suggest that the initial tuning of the tube be performed at something less than normal operating levels, such as 1/3 to 1/2 less than normal beam/mod-anode voltage as a precaution against damaging the tube. Any protection used to prevent damage to the tube certainly has its merits and should be given consideration. However, if the initial tuning is performed at a lower voltage than normal, the klystron must be retuned after applying the normal operating voltages because the klystron detunes with the large voltage change.

SYNCHRONOUS TUNING

1. Follow the manufacturer's suggested procedures in setting up the tube prior to application of voltages and rf drive; e.g., adjusting the split centering plates around external cavity tube pole pieces while in the magnet, or presetting the external cavities to a desired frequency using the tuning charts supplied and adjusting cavity loading loops.

   Internal cavity tubes are usually pretuned to or close to the desired frequency by the manufacturer prior to shipment, so there is no need for a tuning curve and the tubes are self-aligning within their own electromagnets.

2. Apply the correct operating voltages as recommended by the tube manufacturer. If there is to be an initial turn-on and tuning at some lower voltage, the magnet current may also have to be adjusted to minimize the body current.

3. Apply only enough rf drive power at the correct operating frequency to obtain an indication of rf power output; e.g., you should be at least 6 to 8 dB below saturation as indicated by the "X" on Figure 103.

CAUTION

NEVER TUNE THE CAVITIES WITHOUT A
POWER OUTPUT INDICATION ON A METER
OR OSCILLOSCOPE.

4. If there is a VSWR detector or reverse power detector in the input drive line at the klystron input cavity, tune the input cavity for a minimum VSWR or minimum reflected power. You can also tune the

input cavity for a maximum power output indication by observing the output power meter if there is no reverse power meter or VSWR detector in the input line.

If it is difficult to see a power output indication on first application of rf drive power because of the cavities being off frequency, it is permissible to raise the rf drive power to a higher level for a short duration in order to see an indication of rf output, but do not exceed the maximum allowed for any given tube type. If this does not give you some indication of rf output power, return the rf drive to a safer, lower level as other means will have to be used to tune the tube, such as sweeping the tube to locate the frequencies of the cavities.

CAUTION

INDISCRIMINATE TUNING OF ONE OR ALL CAVITIES SHOULD NOT BE DONE.

5. As the output power meter indication rises from tuning, continue to lower the rf drive power so that you just maintain an indication of rf power output.

6. Continue tuning each cavity in sequence (1,2,3,4 and 5 if using a 5 cavity tube), for maximum power output. As each cavity is tuned, the output power increases rapidly as you progress from cavity to cavity. Because of this increase in gain, the rf drive must be lowered to keep the cavity response sharp and to prevent the klystron from becoming overdriven if the drive power was set high at the start of tuning. A rule of thumb is to keep the rf drive low enough so that the output power is about 8 dB below the normal operating rf output power constantly while tuning.

7. When all cavities have been tuned for maximum power output at the low rf drive level, raise the drive level slowly until the tube just saturates (do not go beyond this point). Saturating the tube at this time is done in order to establish a level on the transfer curve, a dB or so below saturation, where the final peaking of all the cavities can be performed. Now lower the rf drive power so the output power is reduced 1 or 2 dB below saturation, then repeak all cavities in sequence again.

CAUTION

BECAUSE OF THE VERY HIGH GAIN OF A KLYSTRON THAT IS SYNCHRONOUSLY TUNED, SOME MANUFACTURERS RECOMMEND THAT YOU SHOULD NOT SATURATE THE TUBE COMPLETELY. THERE MAY BE A POSSIBILITY OF OSCILLATION DUE TO EXTERNAL FEEDBACK OF THE INPUT AND OUTPUT CIRCUITS. GENERALLY, IF ALL SYSTEM COMPONENTS ARE TIGHT THERE SHOULD BE NO PROBLEM WITH OSCILLATIONS.

8. The tube is now synchronously tuned and the drive power can be carefully increased again until the tube saturates. Do not increase the rf drive power beyond the point where the tube saturates, otherwise the rf output power will drop rapidly to a low value as shown in curve "A" of Figure 103. The overall bandwidth for synchronous tuning is rather narrow as illustrated in curve "A" of Figure 104.

9. The bandpass response and penultimate cavity tuning position, both labeled "A" in Figure 104, are representative of the transfer curve labeled "A" in Figure 103.

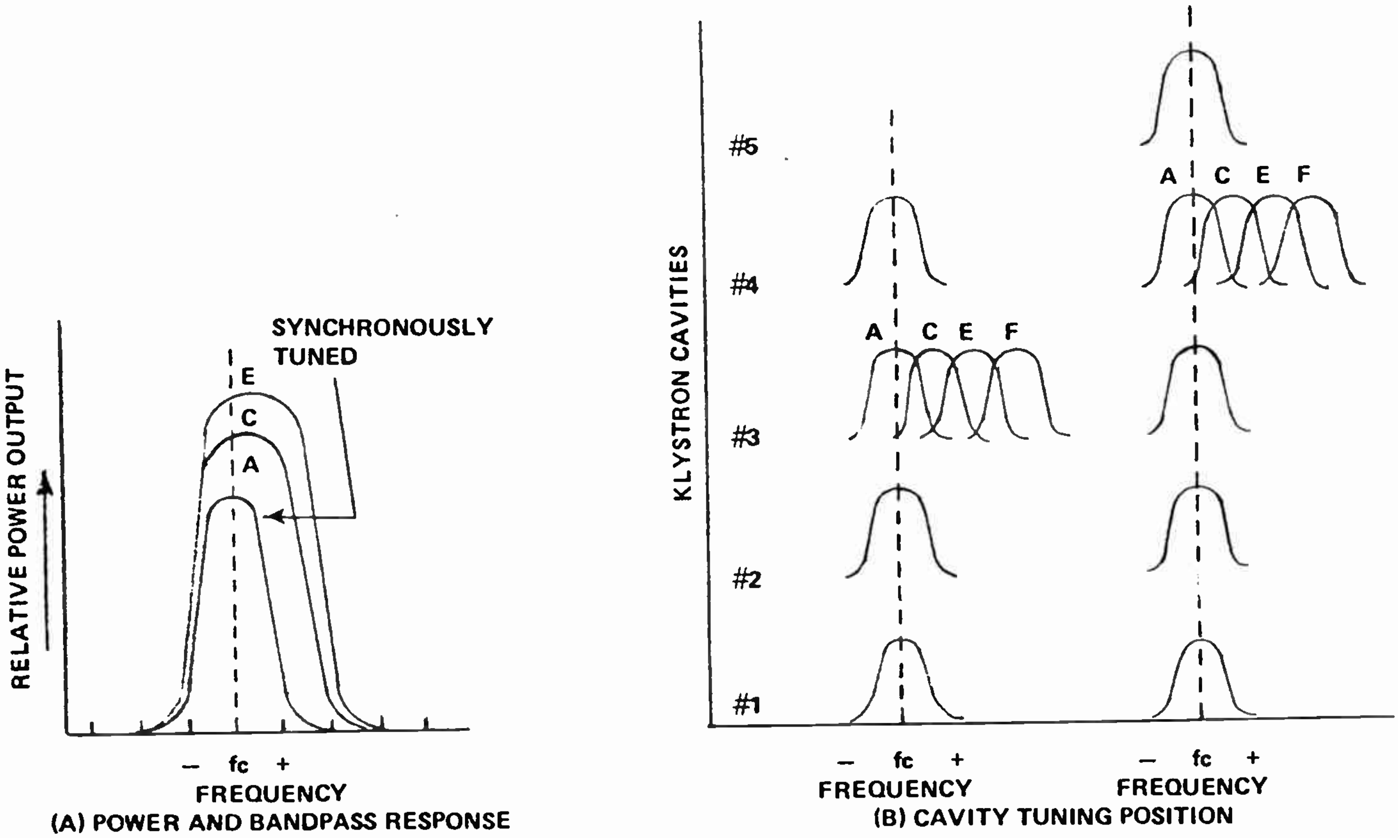


FIGURE 104 : KLYSTRON BANDPASS RESPONSE AND PENULTIMATE CAVITY TUNING POSITION FOR SYNCHRONOUS TO STAGGER/EFFICIENCY TUNING

STAGGER/EFFICIENCY TUNING

Consult the manufacturer's suggested procedures for tuning, such as specific drive power, adjustment of magnet current or adjustment of loading where called for.

10. With the klystron synchronously tuned and with the rf drive power adjusted for saturated power output, the klystron can now be adjusted for stagger/efficiency tuning (the klystron must always be

synchronously tuned first). Now tune the penultimate cavity higher in frequency until the rf output power drops about 2 dB (most klystrons tune clockwise to increase frequency).

CAUTION

MAKE SURE THE PENULTIMATE CAVITY IS TUNED TO THE HIGH FREQUENCY SIDE AND NOT IN THE LOW FREQUENCY DIRECTION. ALSO DO NOT TUNE ANY OTHER CAVITY AT THIS TIME. OTHERWISE THE TUBE WILL HAVE TO BE SYNCHRONOUSLY TUNED AGAIN.

11. Slowly increase the rf drive power again until the output power saturates. You will note that the output power has increased some over the synchronous tuned condition. You are now in a stagger/efficiency tuned condition as indicated by transfer curve "B" in Figure 103. The bandwidth is a little wider than synchronous tuning and the tube requires a little more drive power. There are other levels of staggering which would be dictated by how much power output is desired.

    At this point, external cavity tubes require additional adjustments in the tuning procedure.

12. Refer to Figure 105. Adjust the output coupling for maximum output power, then increase the coupling until the output power reduces between 5 and 10%. Referring to Figure 105, it shows that if the tube is operated in an undercoupled region the tube could be a little unstable.

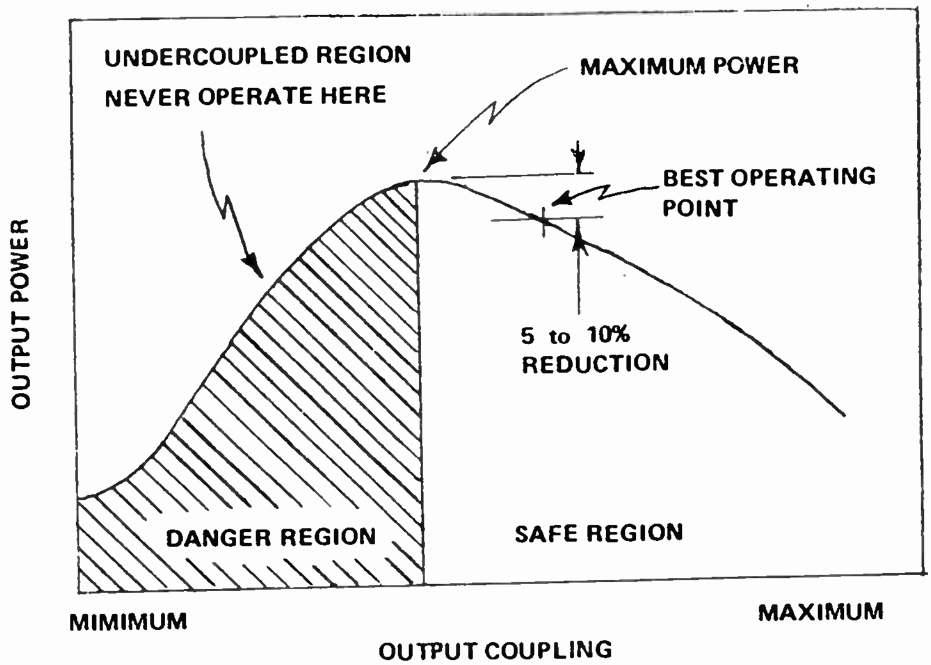


FIGURE 105: ADJUSTMENT OF OUTPUT COUPLING CONTROL ON EXTERNAL CAVITY KLYSTRON

The amount of detuning of the penultimate cavity in this example is purely arbitrary. The intention is to explain the increase in small steps and to illustrate how it changes the rf drive power, power output and bandwidth. In actual practice, the amount of power output desired would give you an idea of how far it would be necessary to detune the penultimate cavity. As you become more familiar with a given tube type you will know from experience how far to detune initially.

13. Power output transfer curves C, D and E are the result of further detuning of the penultimate cavity in the same manner as just described. Always detune the cavity first to the high frequency side (approximately 2 dB drop in power in this example), then increase the rf drive again until the tube saturates. Eventually you will reach a point where the penultimate cavity has been detuned the maximum amount for the particular tube and is still in the bandpass. This is indicated in Figures 103 and 104. You will note

that there is a little increase in bandwidth in each case, an increase in rf power output and a corresponding increase in rf drive up to transfer curve E. Typically there is about 8 to 10 dB more drive required over synchronous conditions.

Any further detuning of the penultimate cavity after this point will only decrease the total rf power output when the drive is increased; this is indicated by curve "F" in Figure 103. In Figure 104A it would fall between bandpass response C and E. Never detune a penultimate cavity past this point, the power will only continue to drop. The penultimate cavity has been detuned to the point where it is being moved out of the total bandpass of the tube and it will not function properly. Continued detuning of the cavity completely out of the bandpass will cause the tube to act as if it had one less cavity. This phenomenon was covered in Section 5.5 on Bunching Action.

Under normal circumstances you will never find yourself in the predicament of detuning a penultimate cavity too far if attention is paid to the tuning. This could be a dangerous situation; aside from possibly losing sight of the fact that the tube has been detuned too far, tuning diaphragms or bellows could be ruptured by excessive detuning (refer to Section 5.2, Cavity Tuning).

In actual practice, it would not be necessary to use as many small steps to detune the penultimate cavity as stated in the example. After some practice, possibly two steps and you will be at the power level desired. Most manufacturers of klystrons or the transmitter usually suggest a beam or mod-anode voltage at which a specific klystron shall be tuned initially for correct operation. Each operator should become familiar with the tube in use before it is arbitrarily detuned too far. How could an operator possibly get into a problem of detuning too far and what is the safest way to return to the correct tuning condition? Let us assume you have detuned the penultimate cavity but you are still lacking the desired power output when you saturate the tube (see Curve D of Figure 103). You have two choices at this point on how to increase power output; one, by increasing the high voltage; or two, by further detuning of the penultimate cavity. Let's further assume you again elect to detune the penultimate cavity to the high frequency side with the thought of gaining more power, but this time the power is a little lower when the tube is saturated (see Curve F of Figure 103). This means you have detuned too far. If this happens, take the following steps: First, it is advisable to return to your last tuning condition or close to it. Lower the drive 3 or 4 dB or to the previous rf drive level, then retune the penultimate cavity carefully in the low frequency direction until the power peaks. Do not tune past the peak.

CAUTION

ALWAYS REDUCE THE RF DRIVE FIRST BEFORE TUNING THE PENULTIMATE CAVITY LOWER IN FREQUENCY WHEN RETUNING IN THE DIRECTION OF SYNCHRONOUS TUNING FROM A STAGGERED CONDITION.

When you have arrived back at the first condition of staggering the penultimate cavity, you may proceed to detune the cavity a little further if desired for more power output, but this time only tune a little further.

This example is a little exaggerated as it is seldom necessary to be so meticulous in tuning for the absolute maximum power. However, there are occasions when it is desirable for this reason: In UHF-TV applications, if a klystron is tuned for something less than maximum efficiency, small changes in rf drive power will cause large changes in output power because the slope of the curve (Po vs Pd) will be steeper. This would be true for either aural or visual operation. Compare the slopes of curves B, C and D with curve E in Figure 103. However, if the tube is tuned correctly at the level the manufacturer has stated, and the power is still low, the beam and/or mod-anode voltage may be raised a little (e.g., 200 or 300 volts); then merely resaturate the tube. If this approach is used, return the rf drive to zero or well below saturation first before raising the high voltage. Then raise the rf drive to saturate the tube again. The magnet current may also have to be slightly adjusted to minimize the body current.

> NOTE: Refer to the earlier discussion on frequency shift in the cavities when the high voltage is changed. A small amount such as 200 or 300 volts may be no problem but it should be checked.

8.5.2 Penultimate Cavity Tuning Precautions

The tuning procedures just described have taken you through a step-by-step sequence for synchronously tuning to the maximum of stagger/efficiency tuning, utilizing the penultimate cavity to gain more power. Obviously, it is not possible to cover all of the many problems that could arise during tuning, however, there are a few basic rules regarding tuning of this cavity that should be related again before continuing with any additional tuning procedure explanations;

1. When tuning a klystron for stagger/efficiency or broadband operation, always detune the penultimate cavity higher in frequency first before increasing the rf drive power.
2. Never tune the penultimate cavity below the center rf drive frequency being used.
3. Never tune the penultimate cavity lower in frequency past the point of saturated power.
4. Always further detune the penultimate cavity higher in frequency before increasing the beam and/or mod-anode voltage or lower the rf drive power to zero or well below saturation first.

Penultimate cavities generally do not have a load circuit to absorb large amounts of energy such as the output cavity; with the exception of the load circuits previously described in Section 5.3, Figure 61 and Section output; one, by increasing the high voltage; or two, by further detuning of the penultimate cavity. Let's further assume you again elect to detune the penultimate cavity to the high frequency side with the thought of gaining more power, but this time the power is a little lower when the tube is saturated (see Curve F of Figure 103). This means you have detuned too far. If this happens, take the following steps: First, it is advisable to return to your last tuning condition or close to it. Lower the drive 3 or 4 dB or to the previous rf drive level, then retune the penultimate cavity carefully in the low frequency direction until the power peaks. Do not tune past the peak.

CAUTION

ALWAYS REDUCE THE RF DRIVE FIRST BEFORE TUNING THE PENULTIMATE CAVITY LOWER IN FREQUENCY WHEN RETUNING IN THE DIRECTION OF SYNCHRONOUS TUNING FROM A STAGGERED CONDITION.

When you have arrived back at the first condition of staggering the penultimate cavity, you may proceed to detune the cavity a little further if desired for more power output, but this time only tune a little further.

This example is a little exaggerated as it is seldom necessary to be so meticulous in tuning for the absolute maximum power. However, there are occasions when it is desirable for this reason: In UHF-TV applications, if a klystron is tuned for something less than maximum efficiency, small changes in rf drive power will cause large changes in output power because the slope of the curve (Po vs Pd) will be steeper. This would be true for either aural or visual operation. Compare the slopes of curves B, C and D with curve E in Figure 103. However, if the tube is tuned correctly at the level the manufacturer has stated, and the power is still low, the beam and/or mod-anode voltage may be raised a little (e.g., 200 or 300 volts); then merely resaturate the tube. If this approach is used, return the rf drive to zero or well below saturation first before raising the high voltage. Then raise the rf drive to saturate the tube again. The magnet current may also have to be slightly adjusted to minimize the body current.

NOTE: Refer to the earlier discussion on frequency shift in the cavities when the high voltage is changed. A small amount such as 200 or 300 volts may be no problem but it should be checked.

8.5.2 Penultimate Cavity Tuning Precautions

The tuning procedures just described have taken you through a step-by-step sequence for synchronously tuning to the maximum of stagger/efficiency tuning, utilizing the penultimate cavity to gain more power. Obviously, it is not possible to cover all of the many problems that could arise during tuning, however, there are a few basic rules regarding tuning of this cavity that should be related again before continuing with any additional tuning procedure explanations;

1. When tuning a klystron for stagger/efficiency or broadband operation, always detune the penultimate cavity higher in frequency first before increasing the rf drive power.
2. Never tune the penultimate cavity below the center rf drive frequency being used.
3. Never tune the penultimate cavity lower in frequency past the point of saturated power.
4. Always further detune the penultimate cavity higher in frequency before increasing the beam and/or mod-anode voltage or lower the rf drive power to zero or well below saturation first.

Penultimate cavities generally do not have a load circuit to absorb large amounts of energy such as the output cavity; with the exception of the load circuits previously described in Section 5.3, Figure 61 and Section

Curve A is representative of the tube as if it were synchronously tuned. Curves B, C and D represent the output power response as the penultimate cavity is detuned and at progressively higher drive levels. Each of the curves show that there is a power peak on the low frequency side of center frequency, but at a lower level from what it would be if the cavity had been tuned correctly in the high frequency direction. What this is really showing you is: that if you were increasing power, going from curve C peak to curve D peak but accidentally tuned in the low frequency direction far enough, you would see a drop in power and then an increase in power, but at a lower level, as you approach the peak below center frequency. Varying the drive power while the penultimate cavity is in the low frequency position would only continue to give you a false indication that you were tuned correctly.

8.5.3 Broadband Tuning

As stated earlier, there is no one specific method for broadbanding a klystron. For each system or tube type, there is a different problem and the tube can only be tuned by careful observance of the instructions which accompany the tube and/or transmitter into the field. For example, with UHF-TV klystrons, the manufacturer's instructions may instruct you to do all tuning at mid-characteristic level such as mid-grey or blanking which is well below saturation. External cavity tubes have necessary adjustments of the output cavity loading during the tuning sequence. If a klystron is designed for broadband communications, you may perform all broadband tuning just below saturation and operate the tube in a saturated condition. For these reasons, among others, it is recommended that the transmitter or tube manufacturer's manual be consulted for specific instructions first before any tuning is performed.

However, a general tuning procedure for broadbanding can be described which will show some of the operations that are common for most all broadband procedures and some specific things to watch for during tuning.

In klystrons that are operated as high powered amplifiers, in particular wide band tubes, the amplifier is normally operated at saturation. It is the saturated bandwidth and efficiency that are important. High level saturation effects can, however, significantly alter the characteristics of the amplifier, consequently broadbanding must be accomplished with this in mind.

When a klystron is adjusted for broadband operation, the voltage gain-bandwidth product of each cavity is proportional to the cavity R/Q, which is a constant that is fixed when the tube is manufactured. The power gain of the complete multi-cavity klystron thus varies very rapidly with the reciprocal of the bandwidth. Since the penultimate cavity has a large effect on the bandwidth, it is always recommended to keep it tuned higher than the rf driving frequency. If it is inadvertently tuned toward the driving frequency, the gain may rise to such a high level that feedback around the associated circuitry can lead to oscillation and possible damage to the tube.

UHF-TV klystrons that are broadbanded for visual service are tuned so they operate well below the saturated output of the klystron during the period of picture information and the overall frequency response must be flat within specified limits. A flat frequency response over a given passband is achieved by proper tuning and loading of the earlier cavities, so that the frequency variation of the current that reaches the output gap will complement the output cavity response over the passband.

The single frequency gain variation of a klystron (output gain vs drive power) is not particularly frequency dependent. The only frequency sensitive components are the resonant cavities, which are linear and the bunching of the electron beam is nearly independent of frequency over the bandwidth of a TV channel. UHF-TV klystrons can be tuned with a swept CW signal so that the response over an 8 MHz bandpass is flat to within 1 dB at all levels from saturation down to -20 dB or lower (see Figure 107).

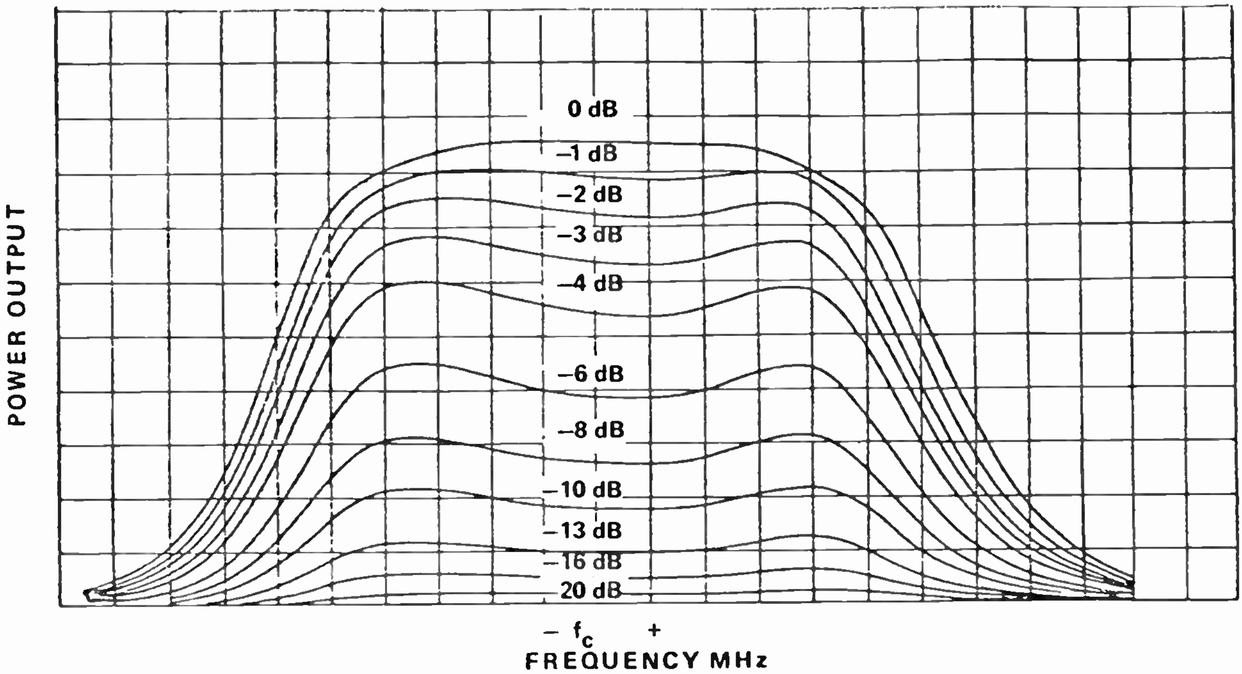


FIGURE 107: TYPICAL KLYSTRON BROADBAND TUNED BANDWIDTH vs RF DRIVE

NOTE: The 8 MHz bandpass refers to the output of the klystron only, which produces both side bands by the modulating process. The undesired portion of the lower sideband is eliminated for TV operation at the transmitter by a vestigial sideband filter so that there is only 6 MHz bandwidth.

This type of test illustrated in Figure 107 is normally performed on every UHF-TV klystron that is produced, and without the hindrance of the usual television bandshaping filters. I've pointed this out because it has been suggested by those who have had initial development experience with color transmitters, that the non-linear response does vary with frequency and that the apparent behavior is connected with the vestigial sideband character of the television signal. It is also suggested that suitable signal processing can counteract the observed frequency dependence.
The two basic tuning patterns that are used for UHF-TV are shown in Figure 108. The graphs illustrate an ideal passband with the tuned positions of

each cavity. In Figure 108A, the resonant frequencies of the cavities are symmetrically distributed about the center of the 8 MHz passband. It is usually easy to obtain a sufficiently flat response using a swept CW signal source. However, if you want the best possible efficiency, the pattern most often used is like the one shown in Figure 108B and 108C for 4 and 5 cavity tubes respectively. Since most of the power in the signal is radiated at the visual carrier frequency, the maximum output power is obtained when the output cavity is correspondingly tuned below the center of the 8 MHz passband at the visual carrier frequency. It will also be necessary to tune the input cavity to a frequency slightly above the channel center in order to maintain an overall flat response.

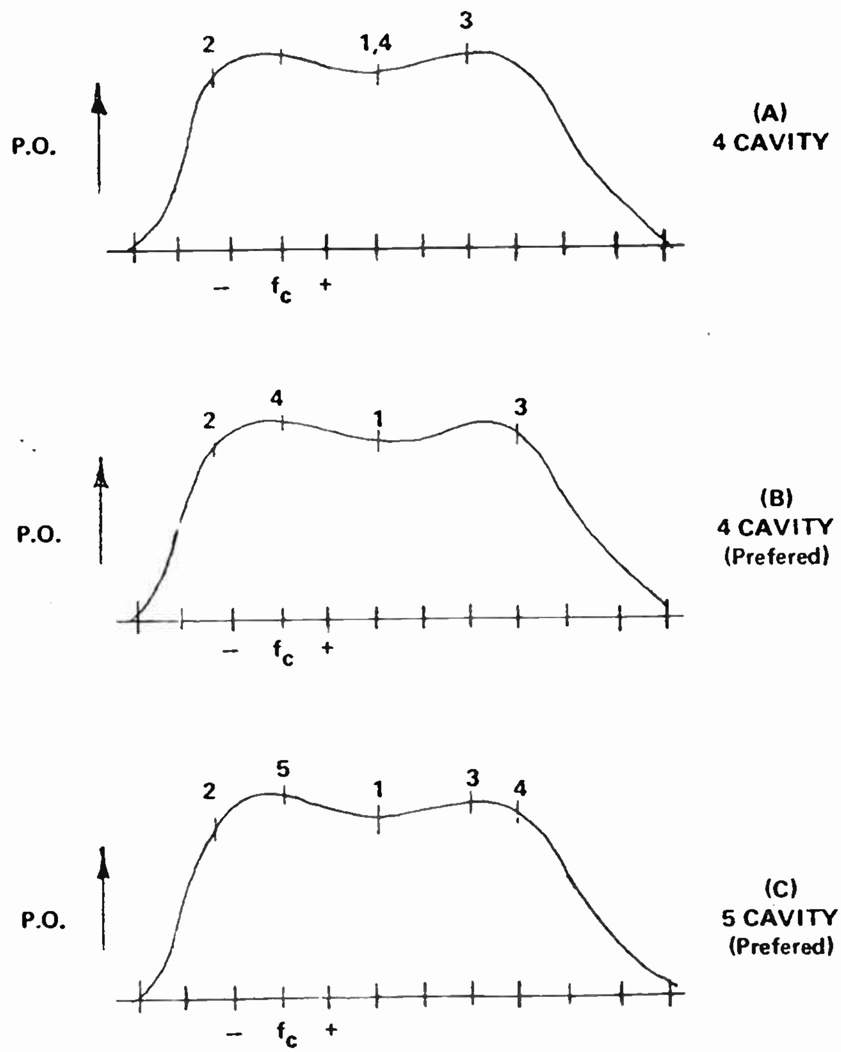


FIGURE 108: FREQUENTLY USED TUNING PATTERNS FOR UHF-TV KLYSTRONS

A question that is often asked at this time; shouldn't the input cavity be tuned so that it appears matched to the rf drive impedance? Since it is necessary to tune the input cavity slightly above the visual carrier (fc), the working Q of this cavity is determined by the neec for a flat frequency response.

It is known that the input cavity can only absorb an incident signal completely if its resonant frequency is the same as the signal frequency. Since the cavity is normally tuned to a frequency above the visual carrier, some of the input carrier power is bound to be reflected. So in normal operation, one should not expect the input cavity to present a perfect match to the rf drive signal.

BROADBAND TUNING

Consult the manufacturers suggested procedures for tuning details which may differ from the one presented here, such parameters as specific drive power operating voltages, frequency shift per cavity and possibly test equipment. The equipment used to produce your swept signal may be a Telonic power source, Marconi Sideband Analyzer or any swept CW source. For this procedure I will only cover the pertinent areas relating to UHF-TV klystrons with an output level between mid-grey and blanking during initial tuning. Each of the figures used for this explanation show the tuning for both 4 and 5 cavity tubes, except one which is for 5 cavity tubes only.

1. Synchronously tune the klystron to the desired carrier frequency as described in paragraph 8.5.1.

2. Detune the penultimate cavity approximately 5 MHz above the high side of the visual carrier. The overall power output of the klystron will now be lower than synchronous tuning. A typical display as viewed on an oscilloscope is shown in Figure 109.

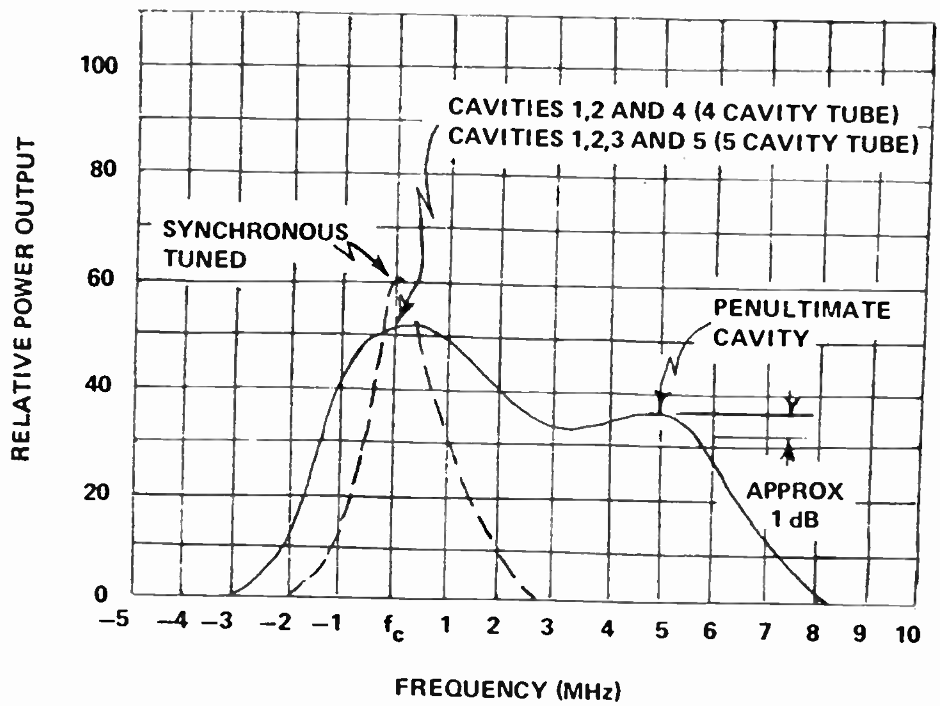


FIGURE 109: OUTPUT REPONSE WITH PENULTIMATE CAVITY TUNED ABOVE CARRIER FREQUENCY

3. Detune the second cavity 1-1/2 MHz below the carrier frequency. A typical response will be as shown in the curve of Figure 110.

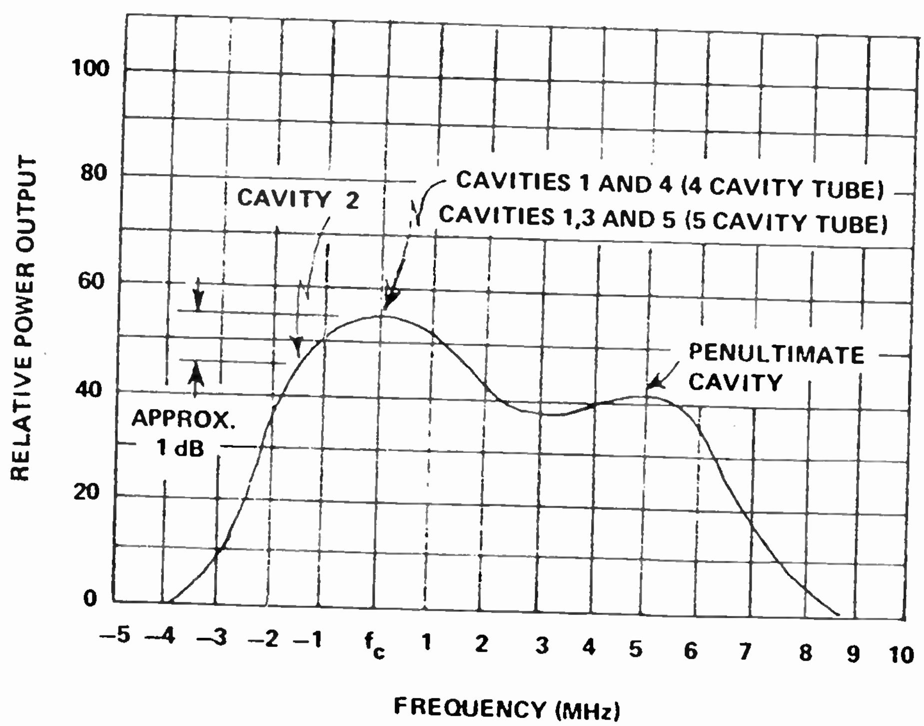


FIGURE 110: OUTPUT RESPONSE WHEN PENULTIMATE AND SECOND CAVITY ARE DETURNED

4. Detune the third cavity (5 cavity tube only) approximately 4 MHz above the visual carrier frequency (refer to Figure 112). This step is omitted for the 4 cavity tube.

5. Detune the first cavity approximately 2 MHz above the visual carrier frequency (see Figure 111).

6. Raise the beam voltage to the required operating level.

7. Raise the rf drive power until the desired output power is reached, such as a mid-characteristic level or any other level that may be suggested by the tube or transmitter manufacturer.

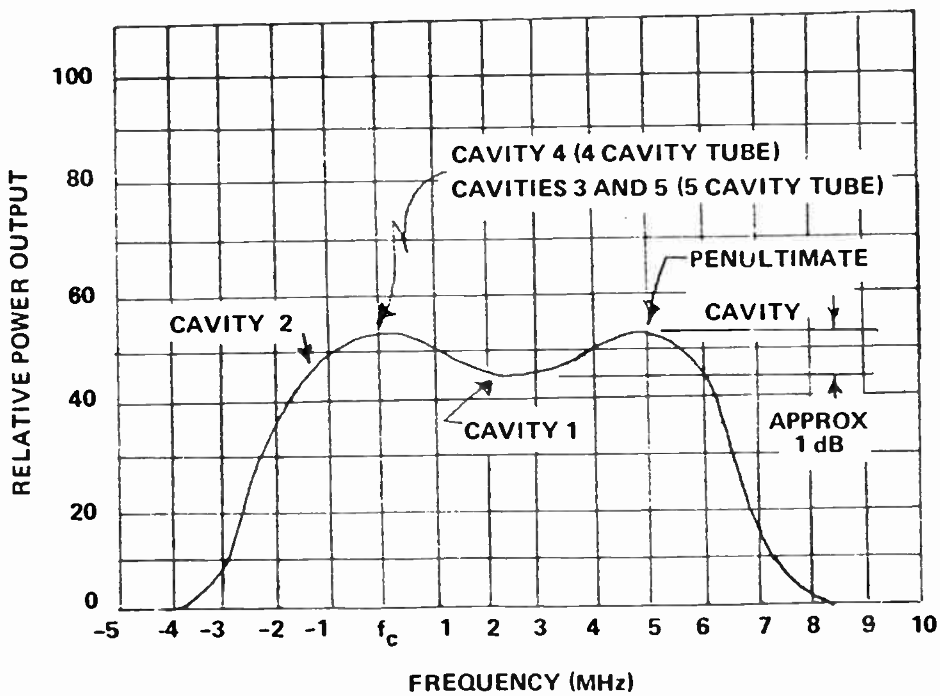


FIGURE 111: OUTPUT RESPONSE WHEN 1st, 2nd AND PENULTIMATE CAVITIES ARE DETUNED

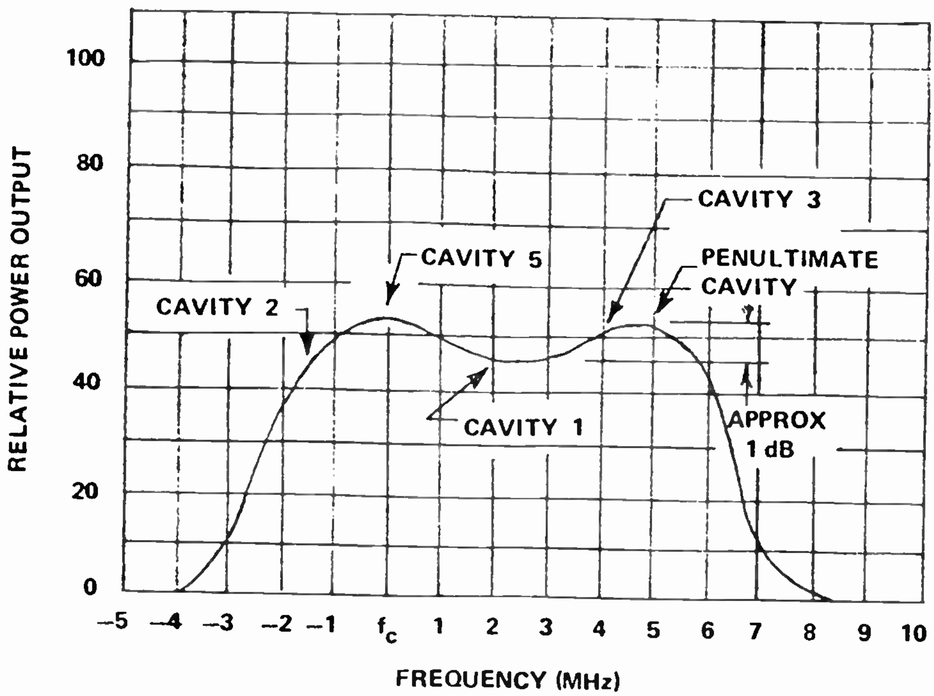


FIGURE 112: OUTPUT RESPONSE (5 CAVITY TUBE) WHEN 1st 2nd, 3rd AND PENULTIMATE CAVITIES ARE DETUNED

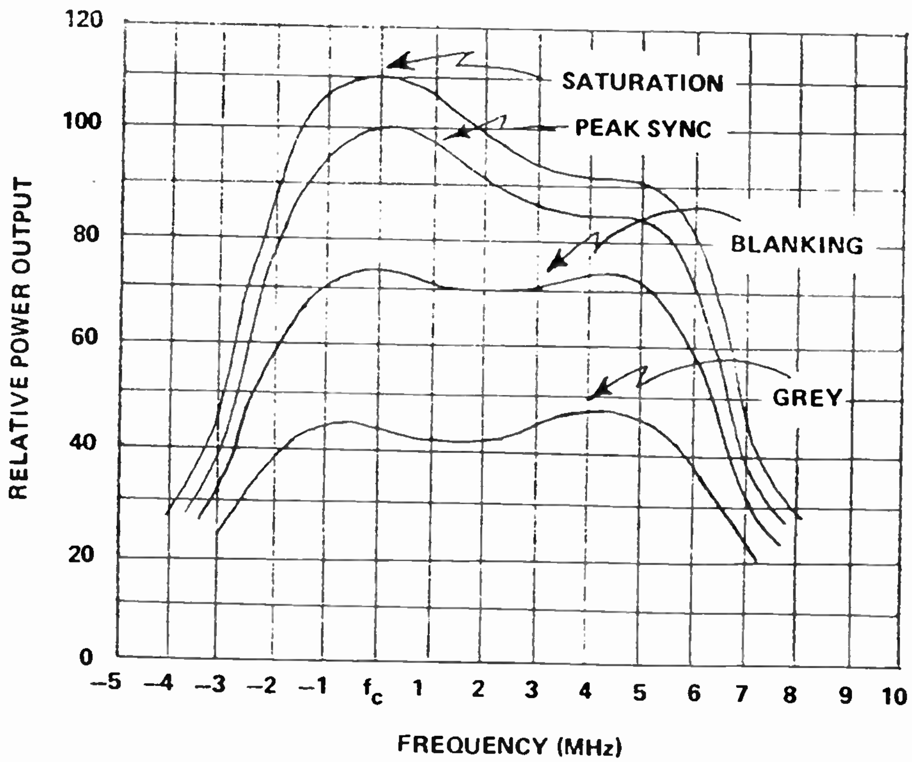


FIGURE 113: OUTPUT RESPONSE OF A KLYSTRON PROPERLY TUNED FOR VISUAL OPERATION

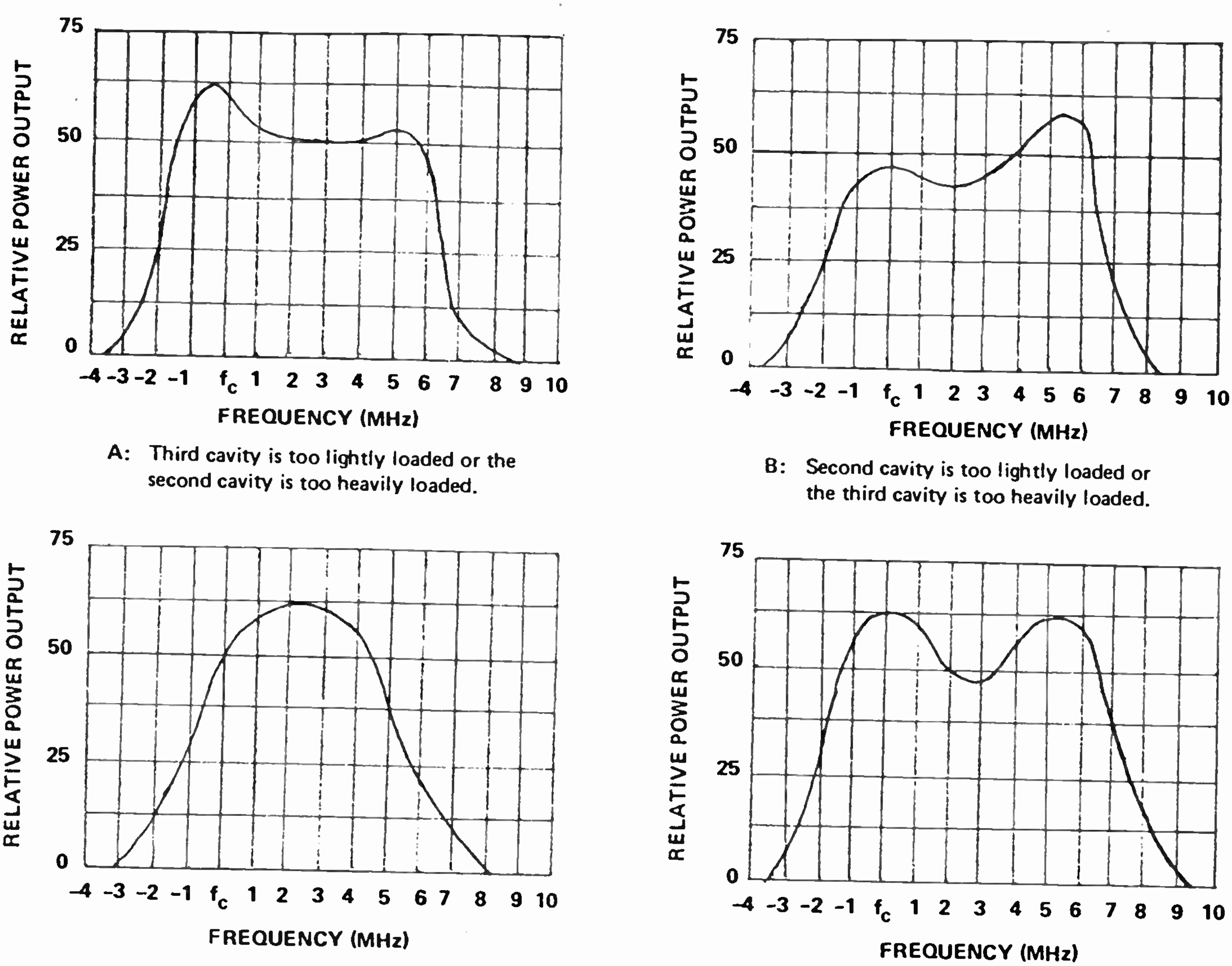
8. Make slight adjustments on the individual cavities to make minor bandpass corrections; i.e., the input or output cavities for slope, the second or penultimate cavities for edge effect and or "holes" (adjust the 3rd also on a 5 cavity tube).

9. The final bandpass should be reasonably flat and lines between white level and blanking and will peak toward the visual carrier at peak-of-sync and saturation (see Figure 113).

10. External cavity tubes may need adjustments on all load couplers in order to obtain the response of Figure 113. Figure 114 A to D illustrates various typical response curves which may result from improper tuning and loading with the usual causes for each curve included under the figure.

11. When the tuning and loading have been corrected on the external cavity tube, the final adjustment is on the output coupling. Adjust for maximum output power, then increase the coupling until the power output decreases between 5 and 10% (refer to Figure 105).

Your klystron is now tuned and ready to operate as a final visual amplifier. Remember, all of the previous tuning should be done under swept conditions and any adjustments performed with a stairstep or multiburst only is not desirable.



A: Third cavity is too lightly loaded or the second cavity is too heavily loaded.

B: Second cavity is too lightly loaded or the third cavity is too heavily loaded.

C: First and/or second cavity are too heavily loaded.

D: First cavity is too lightly loaded or the drive coupling needs adjusting.

FIGURE 114: TYPICAL RESPONSE CURVES WHICH MAY RESULT FROM IMPROPER CAVITY LOADING ON EXTERNAL CAVITY KLYSTRONS

8.5.4 Power Output Measurements

Manufacturers specifications for power output of a klystron, which include UHF-TV klystrons, is based on the power output being measured at the output port of the klystron while operating into a dummy load. Since the previous discussions on drive power and power output were based on average CW drive and power output, the klystrons (aural or visual) may be tested for saturated CW output if desired.

> NOTE: Check with the klystron manufacturers specifications for any restrictions on CW operation.

A simple method is to compare the power value indicated on a rf power measuring device such as a meter, with the power absorbed in a high power water load connected to the klystrons output. The power absorbed in the water load can be calculated from the following:

$$P = 0.264\ (Q)\Delta T^{o}C$$

where:

P = Power in kilowatts
0.264 = Constant for pure water at 30°C
Q = Flow in gallons per minute
ΔT = Difference between inlet and outlet temperature in °C.

Power output from a visual amplifiers klystron may also be measured as peak power. FCC specifications state that the operating power of the visual transmitter is determined at the output terminals of the transmitter, which includes any vestigial sideband and harmonic filters which may be used during normal operation. A dummy load shall be connected at this point as stated above.

During the measurement the transmitter shall be modulated only by a standard synchronizing signal (such as a window test signal) with blanking level set at 75% of peak amplitude as observed on an output monitor, and with this blanking level amplitude maintained throughout the time interval between synchronizing pulses. The average power shall be measured in the same manner as stated above and the peak power shall be calculated by multiplying the average power output by 1.68 as follows:

$$P_o \text{ peak} - 0.264\ (Q)\Delta T^{o}C \times 1.68$$