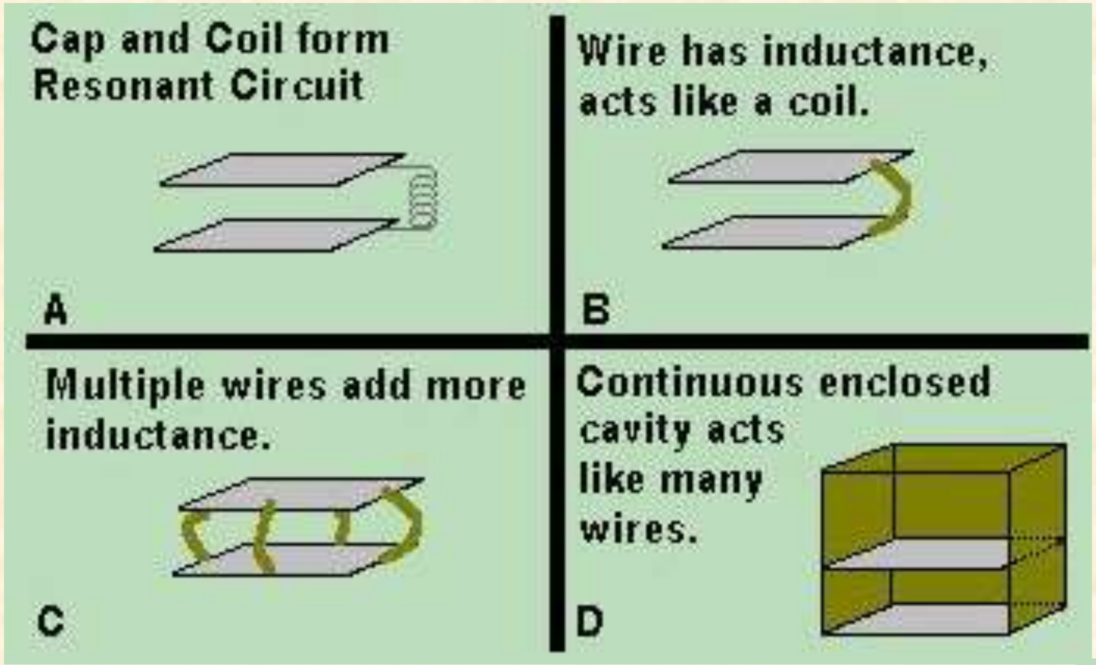
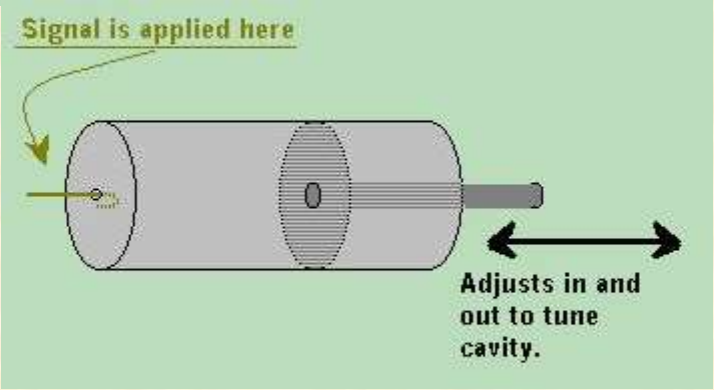
MICROWAVE TUBES

Pre-requisites for Microwave Tubes Topic :

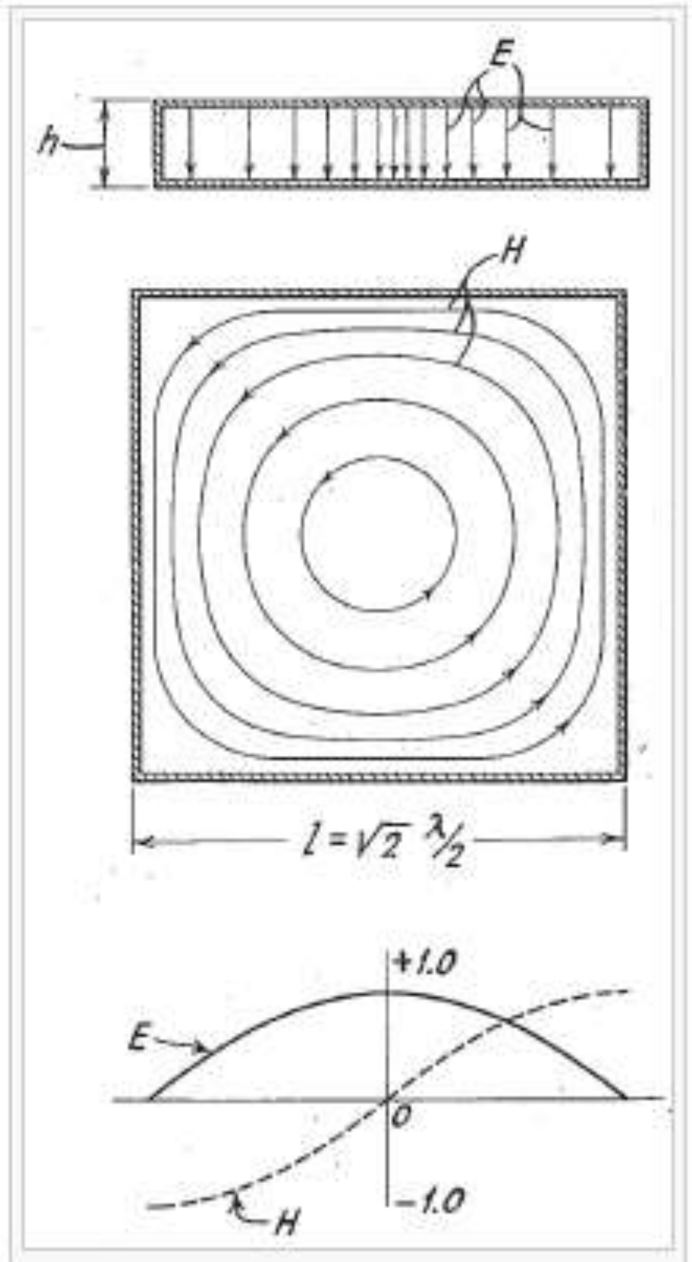
* Transmission media
* Wave guide theory and modes
* Excitation of modes in WGs through probe and loop coupling
* Cavity Resonators
* Vacuum Tube fundamentals

Cavity Resonators



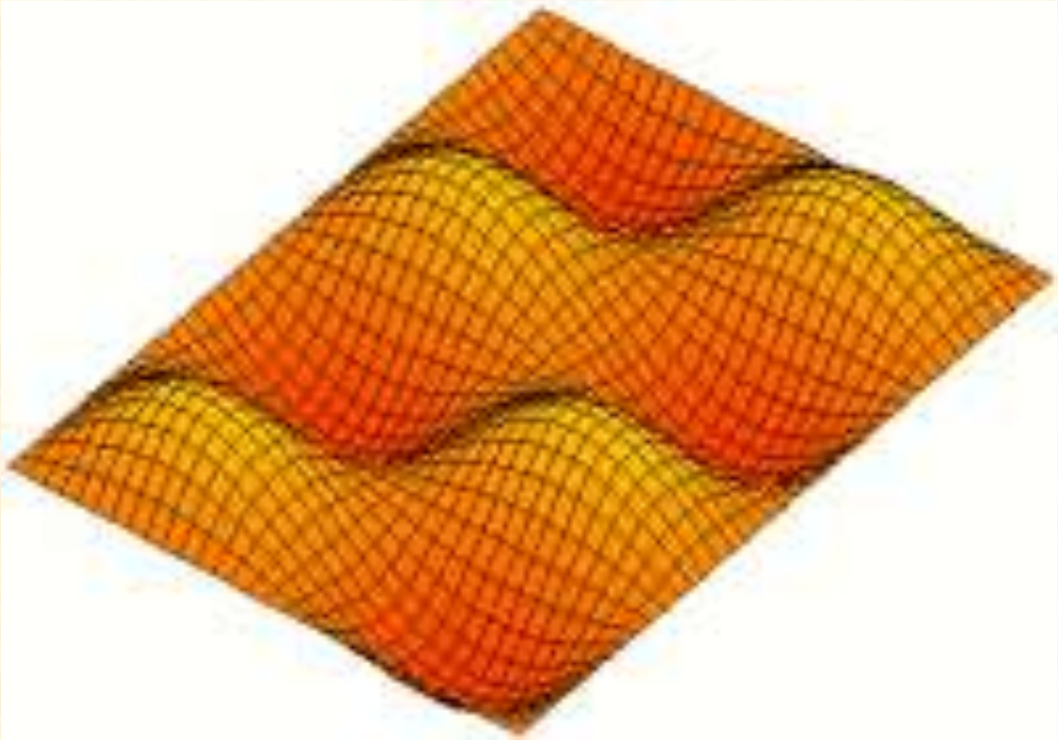


A **cavity resonator**, is one in which the waves exist in a hollow space inside the device. Acoustic cavity resonators in which sound is produced by air vibrating in a cavity with one opening, are known as Helmholtz resonators.



The cavity has interior surfaces which reflect a wave of a specific frequency. When a wave that is resonant with the cavity enters, it bounces back and forth within the cavity, with low loss. As more wave energy enters the cavity, it combines with and **reinforces** the standing wave, increasing its intensity

An illustration of the electric and magnetic field of one of the possible modes in a cavity resonator.



A standing wave in a rectangular cavity resonator.

Rectangular cavity resonators

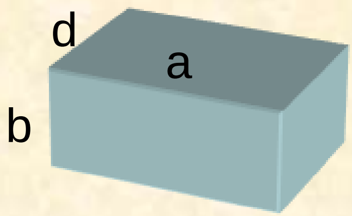
Starting from a rectangular waveguide of cross section ‘a’ by ‘b’ metres, we ca n add short circuit walls in the y-z planes, along the direction of propagation. This gives a rectangular box whose resonant frequency is given by ‘f’

where $(f*\lambda) = c = 3*10^8$, and

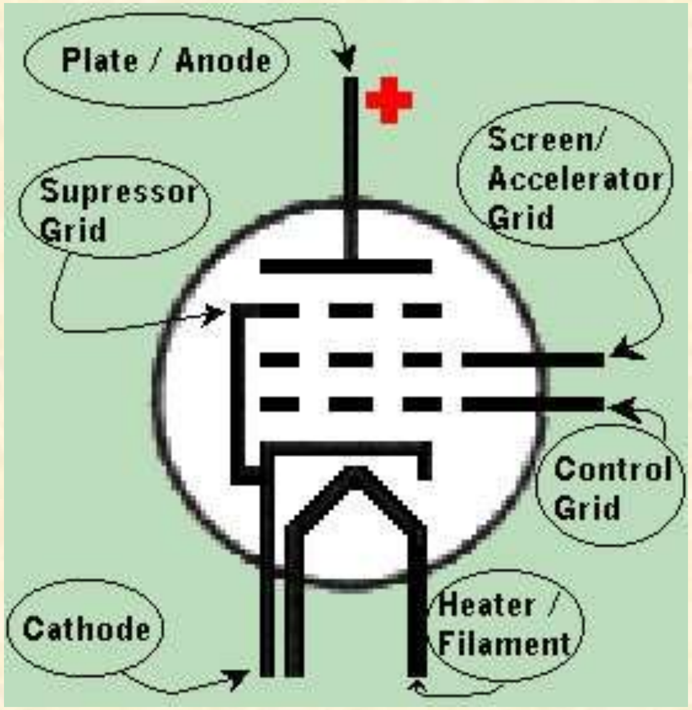
$$1/[\lambda]^2 = \{m/2a\}^2 + \{n/2b\}^2 + \{p/2d\}^2$$

Here, there are m half wavelength loops along x, n half wavelength loops alon g y, and p half wavelength loops along d. It is possible for just one only of the l oop numbers m, n, and p to take the value zero.

The spacings of the walls are d along z, b along y, and a along x. We see ther e are many modes of a rectangular cavity.



Conventional Vacuum Tube



➢ The efficiency of conventional tubes is largely independent of frequency up to a certain limit. When frequency increases beyond that limit, several factors combine to rapidly decrease tube efficiency.

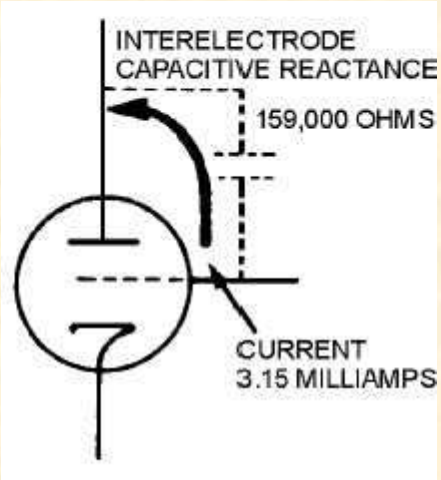
➢ Tubes that are efficient in the microwave range usually operate on the theory of **VELOCITY MODULATION**, a concept that avoids the problems encountered in conventional tubes.

Frequency Limitations of Conventional Tubes

- Three characteristics of ordinary vacuum tubes become increasingly important as frequency rises.
- These characteristics are interelectrode capacitance, lead inductance, and electron transit time.
- The INTERELECTRODE CAPACITANCES in a vacuum tube, at low or medium radio frequencies, produce capacitive reactances that are so large that no serious effects upon tube operation are noticeable. However, as the frequency increases, the reactances become small enough to materially affect the performance of a circuit
- For extremely high-frequency applications (above 1 GHz), the interelectrode capacitances and transit-time delays of standard electron tube construction become prohibitive.
- Transit time effects
- GBW product

For example,

- 1-picofarad capacitor has a reactance of 159,000 ohms at 1 megahertz. If this capacitor was the interelectrode capacitance between the grid and plate of a tube, and the rf voltage between these electrodes was 500 volts, then 3.15 milliamperes of current would flow through the interelectrode capacitance. Current flow in this small amount would not seriously affect circuit performance.



- On the other hand, at a frequency of 100 megahertz the reactance would decrease to approximately 1,590 ohms and, with the same voltage applied, current would increase to 315 milliamperes

Microwave tubes

- A high-vacuum tube designed for operation in the frequency region from approximately 3000 to 300,000 MHz.

- Two considerations distinguish a microwave tube from vacuum tubes used at lower frequencies:

  --- the dimensions of the tube structure in relation to the wavelength of the signal that it generates or amplifies, and the time during which the electrons interact with the microwave field.

Microwave tubes

- In the microwave region wavelengths are in the order of **centimeters**; resonant circuits are in the forms of transmission lines that extend a quarter of a wavelength from the active region of the microwave tube.

- With such short circuit dimensions the internal tube structure constitutes an appreciable portion of the circuit. For these reasons a microwave tube is made to form part of the **resonant circuit**.

- Leads from electrodes to external connections are short, and electrodes are parts of surfaces extending through the envelope directly to the external circuit that is often a **coaxial transmission line** or cavity

- At microwaves the period of signal is in the range of 0.001-1 nanosecond. Only if transit time is less than a quarter of the signal period do significant numbers of electrons exchange appreciable energy with the signal field.

- Transit time is reduced in several ways. Electrodes are closely spaced and made planar in configuration, and high interelectrode voltages are used.

- Tubes designed by the foregoing principles are effective for wavelengths from a few meters to a few centimeters. At shorter wavelengths different principles are necessary.

- To obtain greater exchange of energy between the electron beam and the electromagnetic field several alternative designs have proved practical.

- Instead of collecting the electron beam at a plate formed by the opposite side of the resonant circuit, the beam is allowed to pass into a field-free region before reacting further with an external circuit.

- The electron cloud can be deflected by a strong static magnetic field so as to revolve and thereby react several times with the signal field before reaching the plate. (Klystron; Magnetron.)

- Instead of producing the field in one or several resonant circuits, the field can be supported by a distributed structure along which it moves at a velocity comparable to the velocity of electrons in the beam.

- The electron beam is then directed close to this structure so that beam and field interact over an extended interval of time. (Traveling-wave tube.)

However, there seems to be no end to the creative ways in which tubes may be constructed,

MW TUBES

- Klystron Amplifier
- Klystron Oscillator
- Magnetron Oscillator
- Cross Field Amplifier (CFA)
- TWT Amplifier
- Backward Wave Oscillator (BWO)

Applications of high power devices at millimeter wave frequency rang e

- ✓ **Radar (long-range and high resolution)**
- ✓ **Communication (high information density)**
- ✓ **Electronic warfare**
- ✓ **Directed energy weaponry**
- ✓ **Material processing**
- ✓ **Waste remediation**
- ✓ **Ozone generation**
- ✓ **Atmospheric purification of admixtures like freons that destroy ozone layer**

Microwave Tubes

- **Linear Beam Devices**
  - **Resonant Cavity**
    - **Klystron Amplifier**
      - **Reflex Klystron**
  - **slow-wave structure (non-resonant)**
    - **Forward Wave**
      - **Helix TWT**
        - **Coupled Cavity TWT**
    - **Backward Wave**
      - BWA
      - BWO
- **Cross Field Devices**
  - **Magnetron**
  - **CFA**

MICROWAVE SOURCES

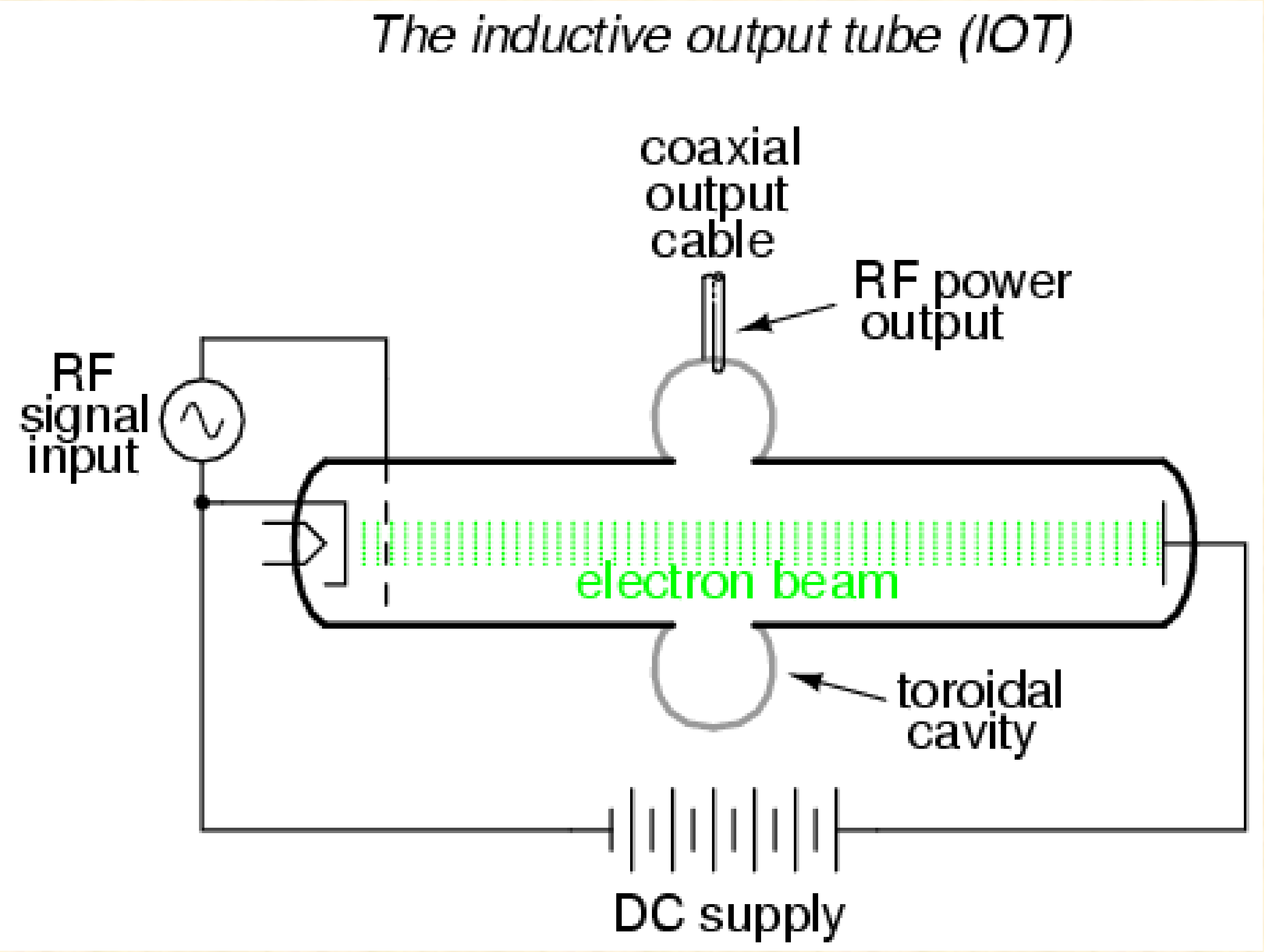
High Power Microwave Tubes

1. Cross Field Devices : Orthogonal Electric and Magnetic fi elds:- Magnetron, CFA -- As Low power amplifiers in coher ent MTI, pulse compression radar, Pulse Doppler

2. Linear Beam Devices: Continuous electron beam in the i nteraction region :- Klystron, TWT.

RF conversion efficiency = ratio of RF power output availa ble to the dc power input

RF conversion efficiency of RF Power sources : 10% to 60 %

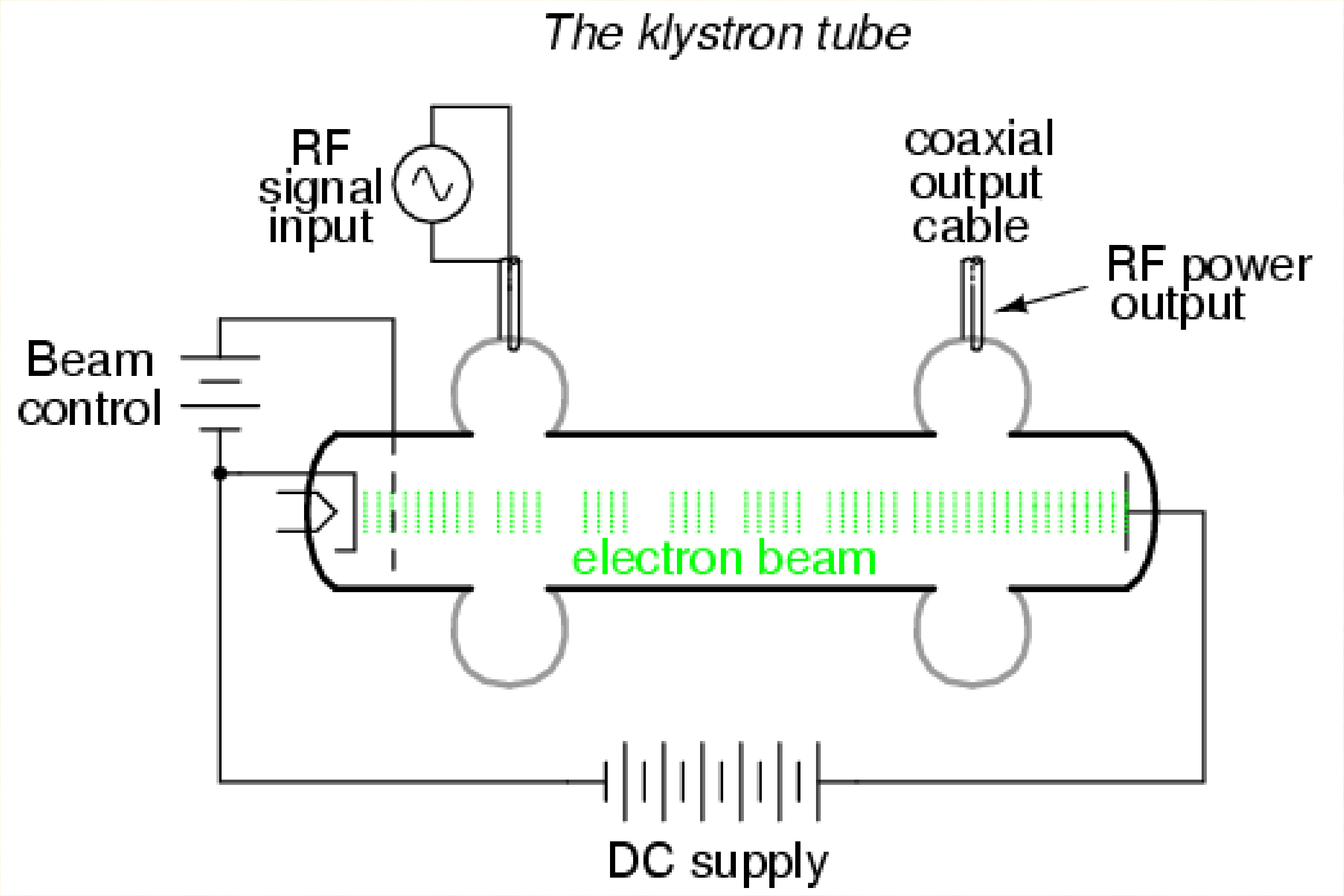


Two of the researchers instrumental in the initial development of the IOT, a pair of brothers named **Sigurd and Russell Varian**

Inductive Output Tube (IOT)

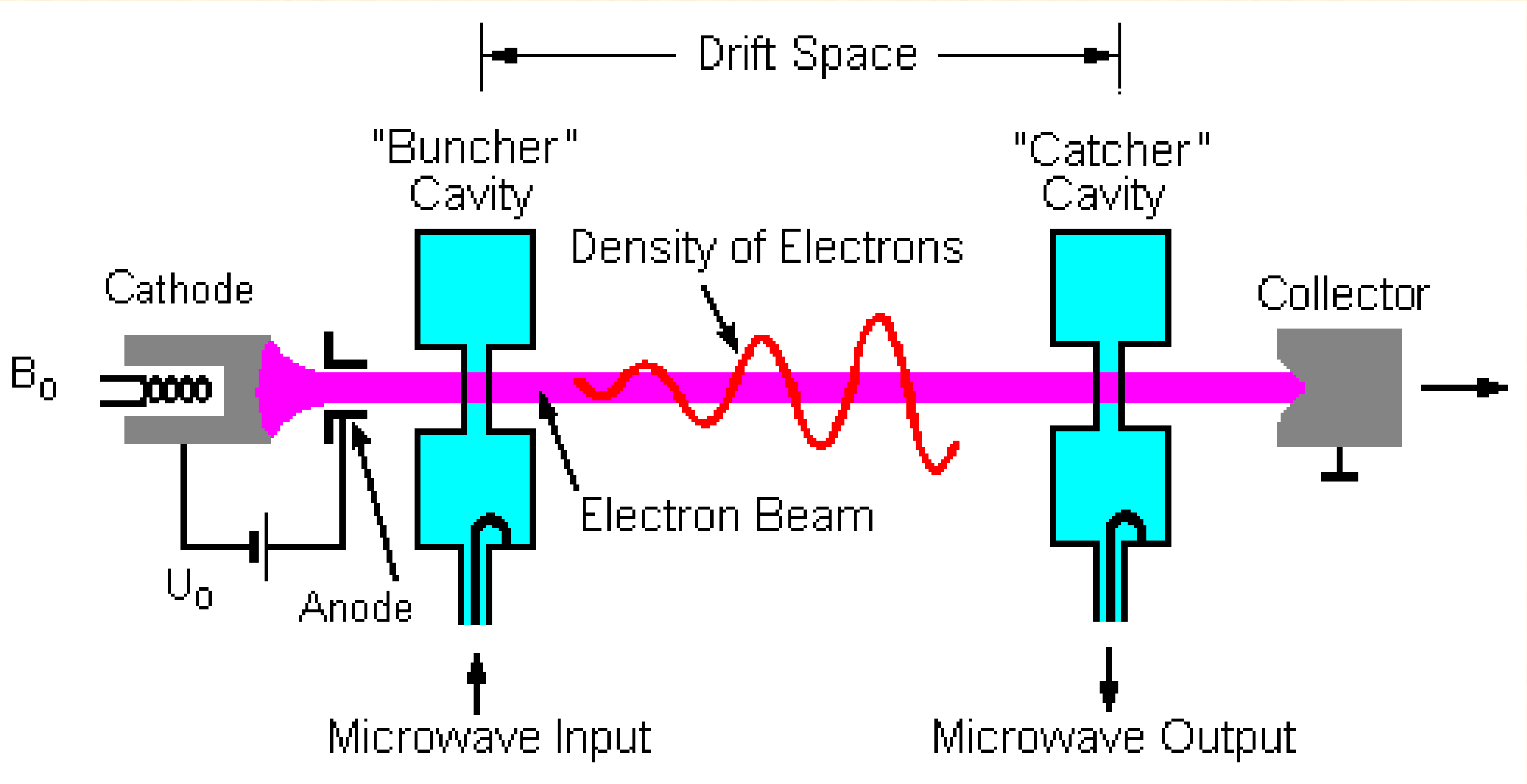
- It was discovered in 1939 that a **toroidal cavity** made of conductive material called a ***cavity resonator*** surrounding an <u>electron beam of oscillating intensity</u> could extract power from the beam without actually intercepting the beam itself.

- The oscillating electric and magnetic fields associated with the beam "echoed" inside the cavity, in a manner similar to the sounds of traveling automobiles echoing in a roadside canyon, allowing radio-frequency energy to be transferred from the beam to a waveguide or coaxial cable connected to the resonator with a coupling loop.



This input resonator acted as a pair of inductive grids to alternately "bunch" and release packets of electrons down the drift space of the tube, so the electron beam would be composed of electrons traveling at different velocities. This "velocity modulation" of the beam translated into the same sort of amplitude variation at the output resonator, where energy was extracted from the beam. The Varian brothers called their invention a *klystron*.

Two Cavity Klystron Amplifier

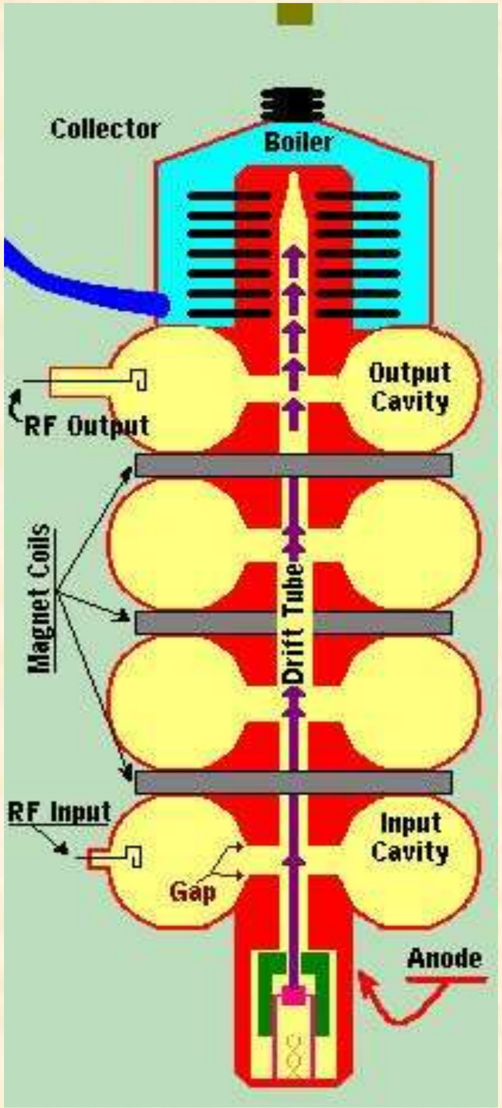


- It is not uncommon to see a klystron with a beam current of 25 THOUSAND VOLTS (that’s 25KV) at 5 Amps. Now if'n I done my math correctly, P=IE, so Power Out = 25,000 multiplied by 5. This tube would have a beam power of 125,000 Watts.

- You don't have to touch anything! There is so much electrical potential built up in the surrounding air that your hair stands on end just being around that sort of voltage.

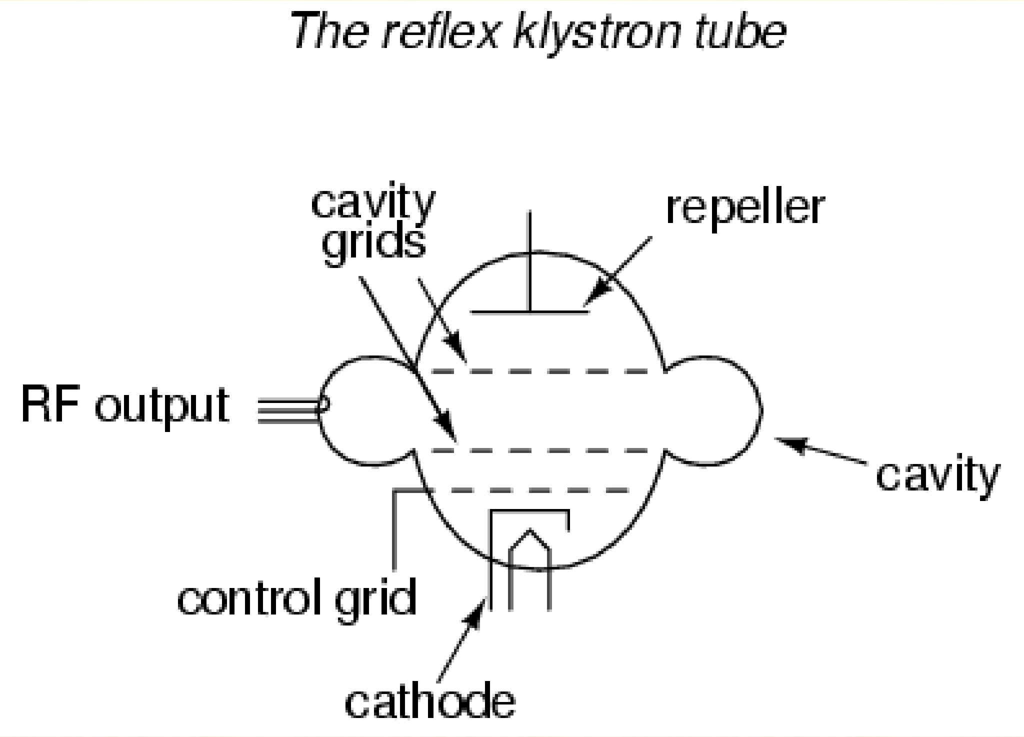
- the beam must be carefully guided up through the drift tube until it reaches it's final resting place. This is usually done with electromagnetic coils. Magnet supply voltages are commonly in the 200 Volt range.

- New and recent development of a special type of klystron using fixed permanent magnets, called a PPM Focused Klystron which was able to obtain power levels on the order of 50 Megawatts.



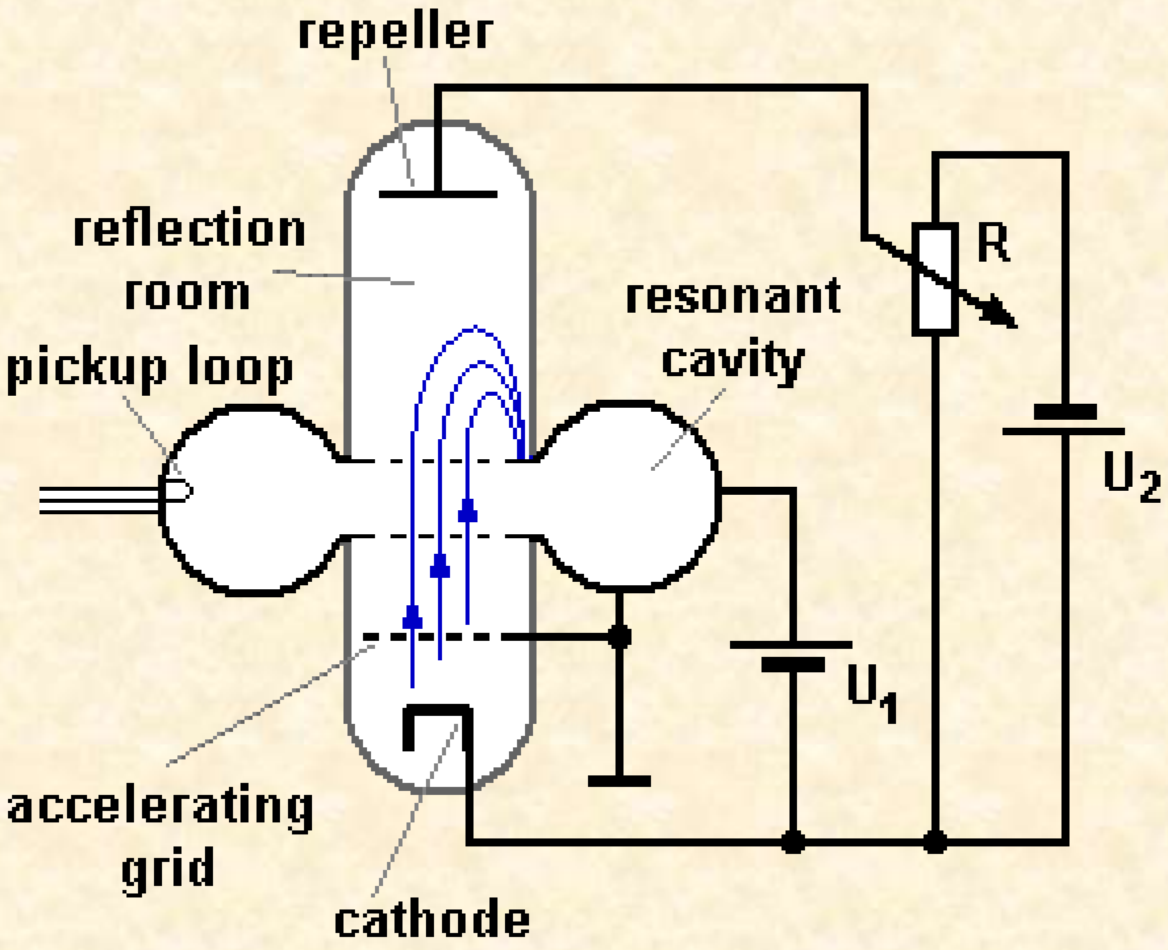
Super power Klystron used at the Canberra Deep Space Communications Complex

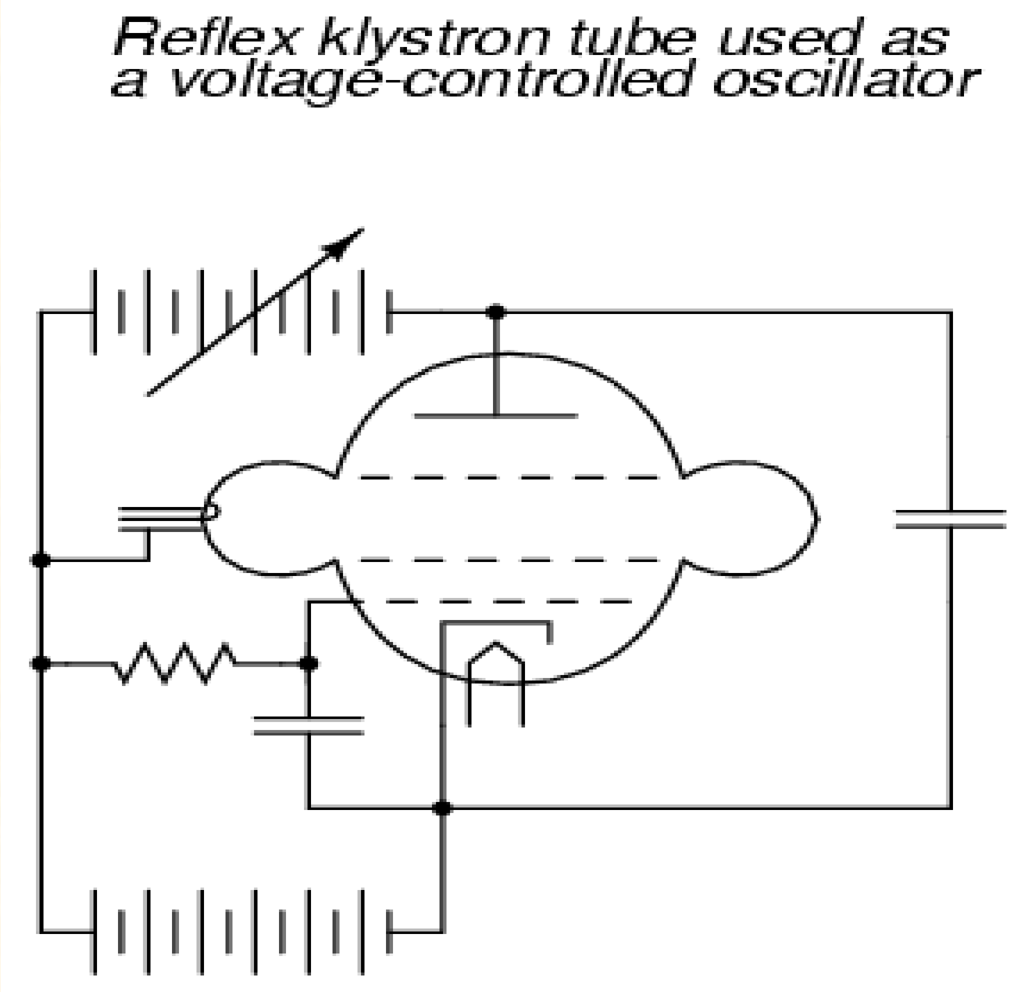
Multi-cavity Klystron



Electrons emitted from the heated cathode travel through the cavity grids toward the repeller plate, then are repelled and returned back the way they came (hence the name *reflex*) through the cavity grids. Self-sustaining oscillations would develop in this tube, the frequency of which could be changed by adjusting the repeller voltage. Hence, this tube operated as a voltage-controlled oscillator.

Reflex Klystron





As a voltage-controlled oscillator, reflex klystron tubes served commonly as "l ocal oscillators" for radar equipment and microwave receivers

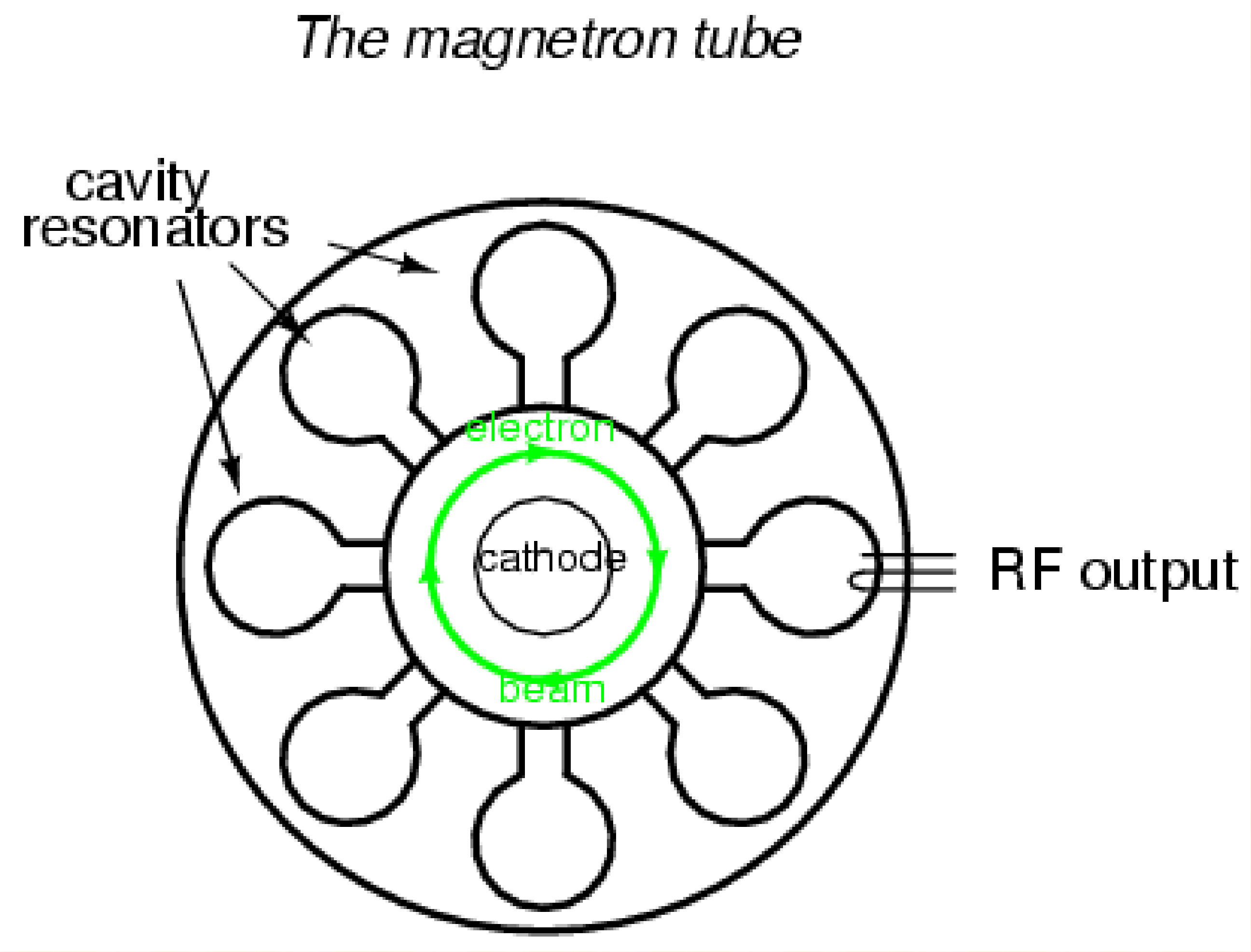
- Initially developed as low-power devices whose output required furt her amplification for radio transmitter use, reflex klystron design was refined to the point where the tubes could serve as power devices in t heir own right.

- Reflex klystrons have since been superseded by semiconductor de vices in the application of local oscillators, but amplification klystrons continue to find use in high-power, high-frequency radio transmitters and in scientific research applications.

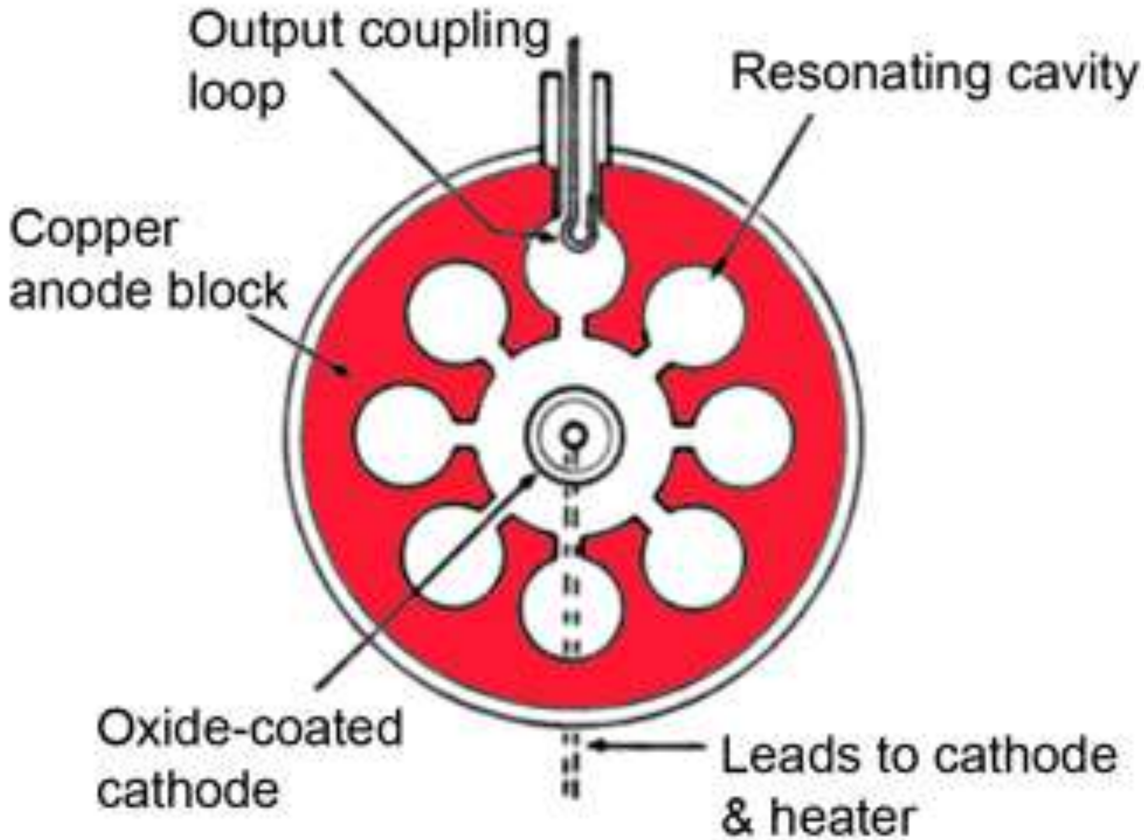
- Reflex oscillators are used as signal sources from 3 to 200 GHz. The y are also used as the transmitter tubes in line-of-sight radio relay sys tems and in low-power radars

Magnetron tube

- One microwave tube performs its task so well and so cost-effectively that it continues to reign supreme in the competitive realm of consu mer electronics: the magnetron tube.
- This device forms the heart of every microwave oven, generating se veral hundred watts of microwave RF energy used to heat food and beverages, and doing so under the most grueling conditions for a tu be: powered on and off at random times and for random durations.
- Magnetron tubes are representative of an entirely different kind of tu be than the IOT and klystron. Whereas the latter tubes use a linear e lectron beam, the magnetron directs its electron beam in a circular p attern by means of a strong magnetic field:

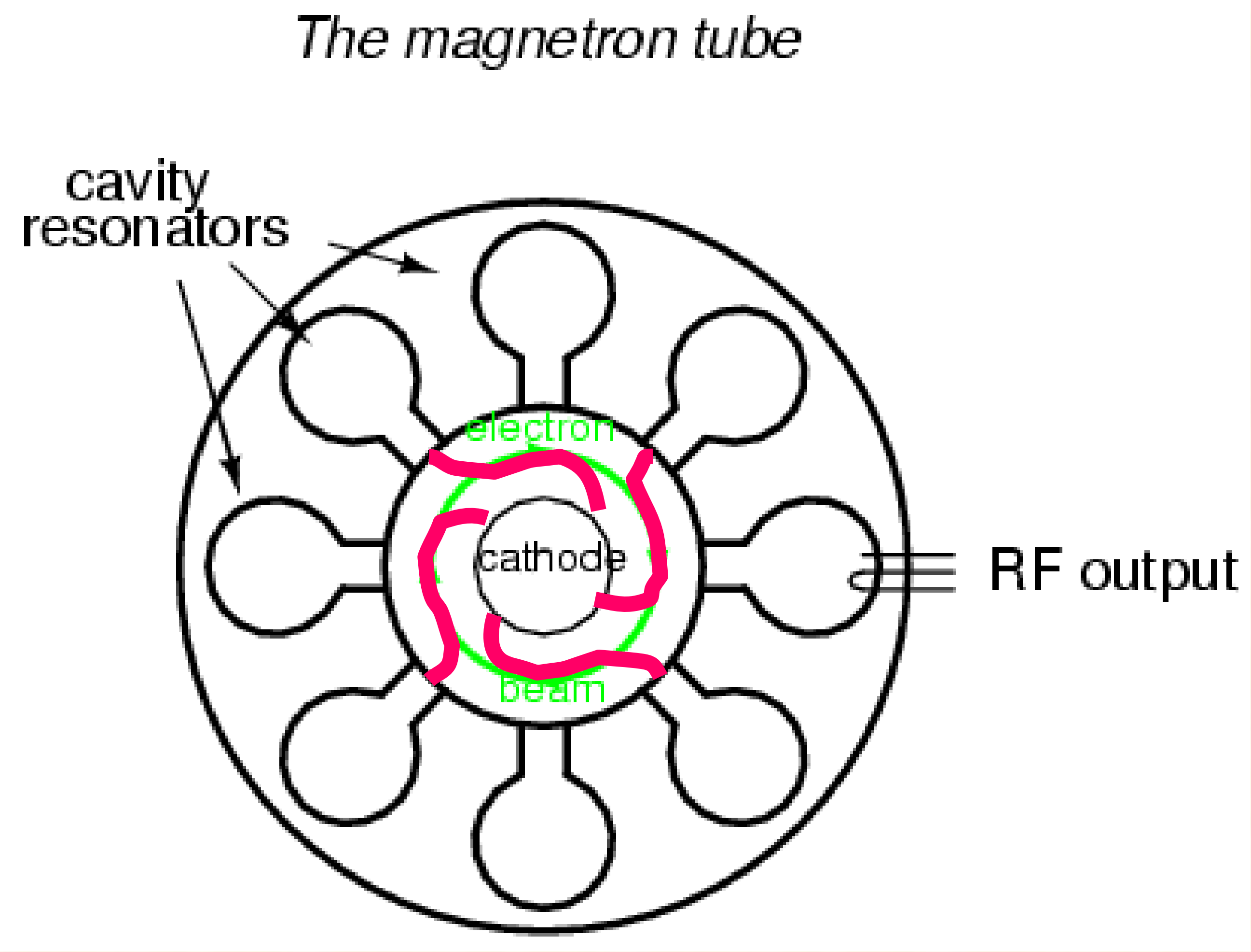


Magnetic flux runs perpendicular to the plane of the circular electron path. In other words, from the view of the tube shown in the diagram, you are looking straight at one of the magnetic poles.



Resonant cavity magnetron high-power
high-frequency oscillator

A cross-sectional diagram of a resonant cavity magnetron. Magnetic field is perpendicular to the plane of the diagram



Magnetic flux runs perpendicular to the plane of the circular electron path. In other words, from the view of the tube shown in the diagram, you are looking straight at one of the magnetic poles.

- Cavity resonators are used as microwave-frequency "tan k circuits," extracting energy from the passing electron b eam inductively.

- Like all microwave-frequency devices using a cavity reso nator, at least one of the resonator cavities is tapped wit h a *coupling loop*:

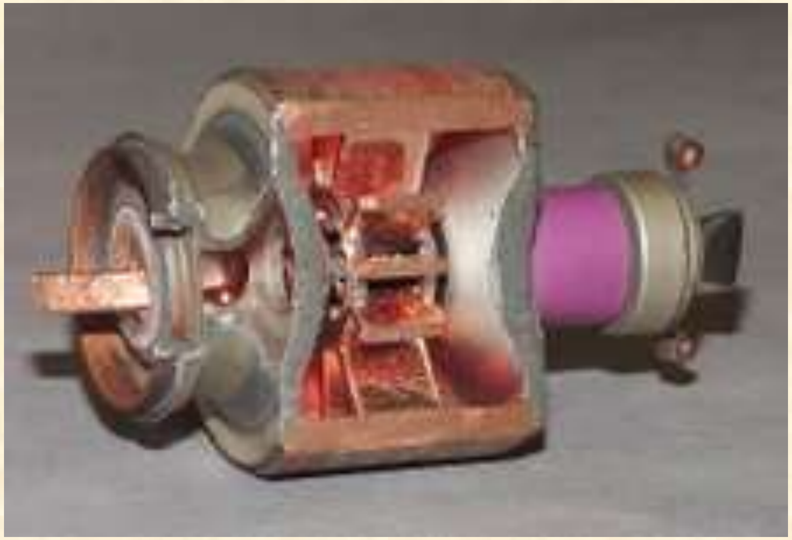
- A loop of wire magnetically coupling the coaxial cable to the resonant structure of the cavity, allowing RF power to be directed out of the tube to a load.

- In the case of the microwave oven, the output power is di rected through a waveguide to the food or drink to be he ated, the water molecules within acting as tiny load resist ors, dissipating the electrical energy in the form of heat.

- Magnetrons have been used since the 1940s as pulsed microwave radiation sources for radar tracking.

- Because of their compactness and the high efficiency with which they can emit short bursts of megawatt peak output power, they have proved excellent for installation in aircraft as well as in ground radar stations.

- In continuous operation, a magnetron can produce a kilowatt of microwave power which is appropriate for rapid microwave cooking.



Magnetron with magnet in it s mounting box. The horizo ntal plates form a Heatsink, cooled by airflow from a fan

Magnetron with section removed (magnet is not shown)

Health hazards

- Among more speculative hazards, at least one in particular is well n and documented.

- As the lens of the eye has no cooling blood flow, it is particularly prone to overheating when exposed to microwave radiation. This heating can in turn lead to a higher incidence of cataracts in later life. A **microwave oven** with a warped door or poor microwave sealing can be hazardous.

- There is also a considerable electrical hazard around magnetrons, as the y require a high voltage power supply. Operating a magnetron with the prot ective covers and interlocks bypassed should therefore be avoided.

- Some magnetrons have ceramic insulators with a bit of beryllium oxide Th e beryllium in this ceramic is a serious chemical hazard if crushed and inhal ed, or otherwise ingested. Single or chronic exposure can lead to berylliosis , an incurable lung condition. In addition, beryllia is listed as a confirmed hu man carcinogen by the IARC; therefore, broken ceramic insulators or magn etrons should not be directly handled.

Traveling Wave Tube (TWT)

- The traveling wave tube (TWT) is an electron tube used for amplification at microwave frequencies – generally identified as frequencies between 500 MHz and 300 GHz or to wavelengths measured from 30 cm to 1 mm.

- The TWT is not a new device. Its remarkable capabilities and some of its potential applications have been known for nearly 60 years.

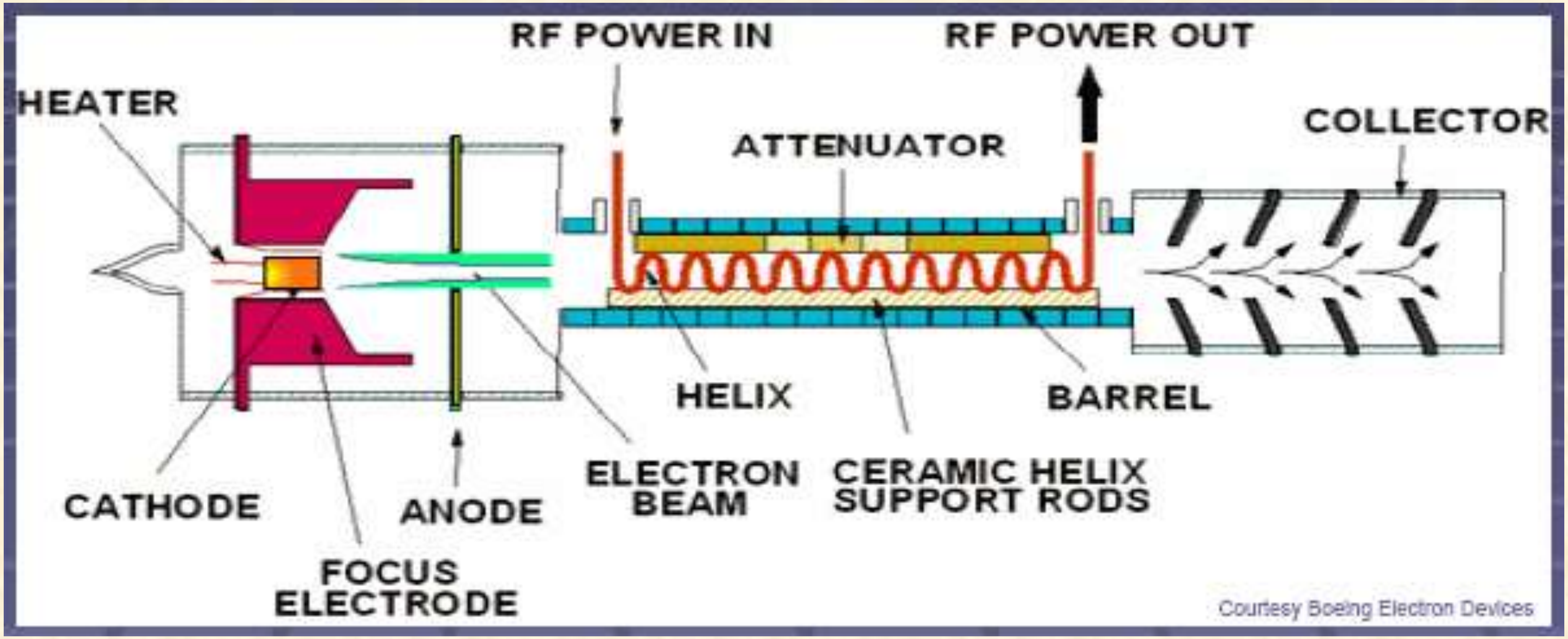
- It was invented during the latter part of World War II by an Austrian refugee, Dr. Rudolf Kompfner, while working on microwave tubes for the British Admiralty.

- Power generation capabilities range from watts to megawatts.

- For helix TWTs, bandwidths may be as high as two octaves or more and power levels of tens to hundreds of watts

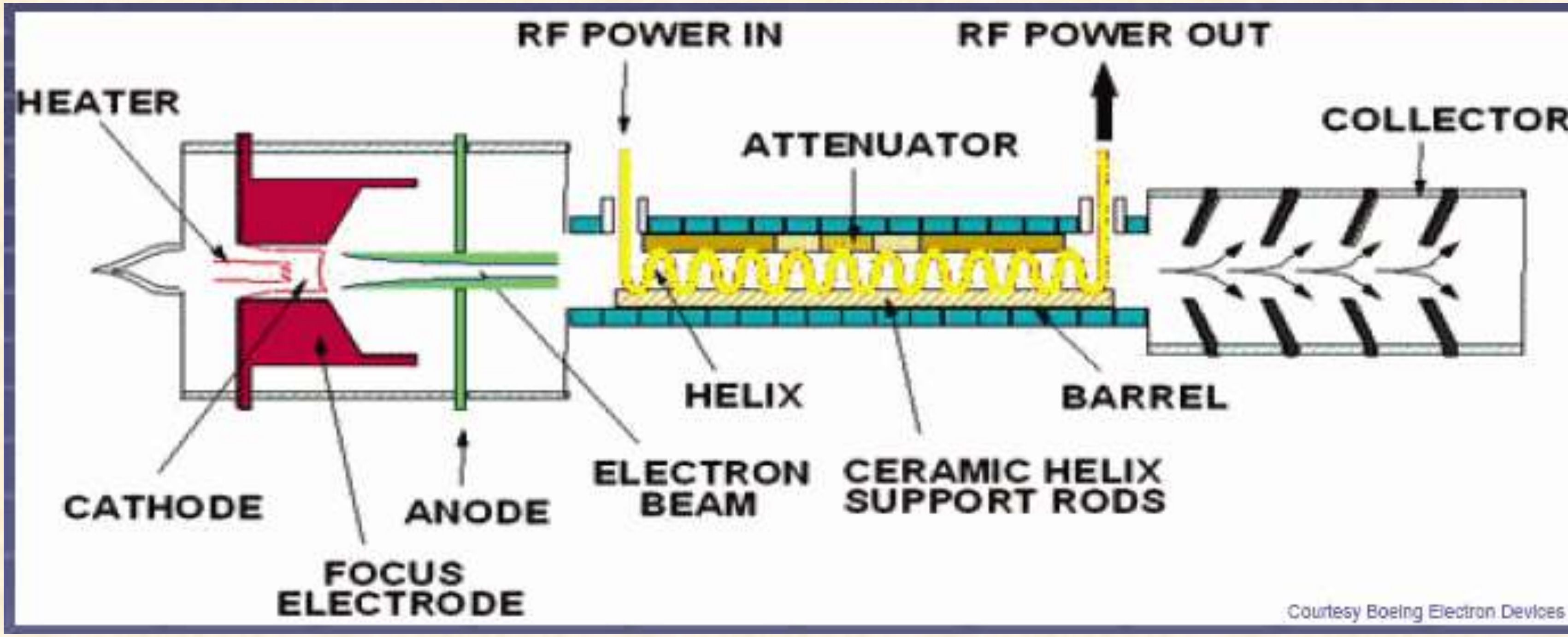
- For coupled-cavity TWTs, bandwidths in the 10 – 20% range are common with power levels in the megawatt levels.

Components of a TWT



- At the left of this diagram is an electron gun assembly.
- The **cathode**, when heated, emits a continuous stream of electrons.
- These electrons are drawn through an aperture in the **anode** and are then focused into a well-defined cylindrical beam by a magnetic field.
- The beam is thereby caused to travel inside the slow-wave circuit for the length of the tube.
- The electrons are finally collected and their kinetic energy is dissipated in the form of heat in the **collector**.

Wave – Beam Interaction



- At the same time that the cylindrical electron beam is moving along the lengt h of the tube axis, the RF signal to be amplified is fed into the slow-wave structur e consisting, in this case, of a coiled wire called a **helix**.

- The RF energy travels along the **helix wire** at the velocity of light. However, because of the helical path, the energy progresses along the axial length of the t ube at a considerably lower axial velocity, determined primarily by the pitch and diameter of the helix

Specific Applications and TWT Design Trade-Offs

- The design of a TWT originates with the requirements to provide certain amounts of gain and power over a certain frequency band

- These considerations lead to trade-offs that affect each of the major subassemblies of the TWT. Those considerations include:

- Type of slow-wave circuit to be used in meeting the power and bandwidth requirements, including the selection of cathode voltage and current to be used in meeting those requirements.

- It is important to note that the higher thermal dissipation capability in coup led-cavity TWT circuits can provide two orders of magnitude and greater po wer output capability than available from TWTs having helix circuits, at the penalty of increased size and weight;

- Method to be employed for focusing the electron beam;

- Method to be used for varying the beam current, including the method use d for turning the TWT on and off as well as any modulation required during TWT operation;

contd…

- Operating life requirements;
- Environmental conditions under which the TWT will operate (ambient pressure, ambi ent temperature, shock and vibration level s, etc.);
- Type of cooling available;
- Size and weight limitations;
- Cost.

Crossed-Field Amplifier

- A (CFA) is a specialized vacuum tube, first introduced in the mid-1950s and frequently used as a microwave amplifier in very-high-power transmitters.

- A CFA has lower gain and bandwidth than other microwave amplifier tubes (such as klystrons or traveling wave tubes); but it is more efficient and capable of much higher output power.

- Peak output powers of many megawatts and average power levels of tens of kilowatts can be achieved, with efficiency ratings in excess of 70 percent

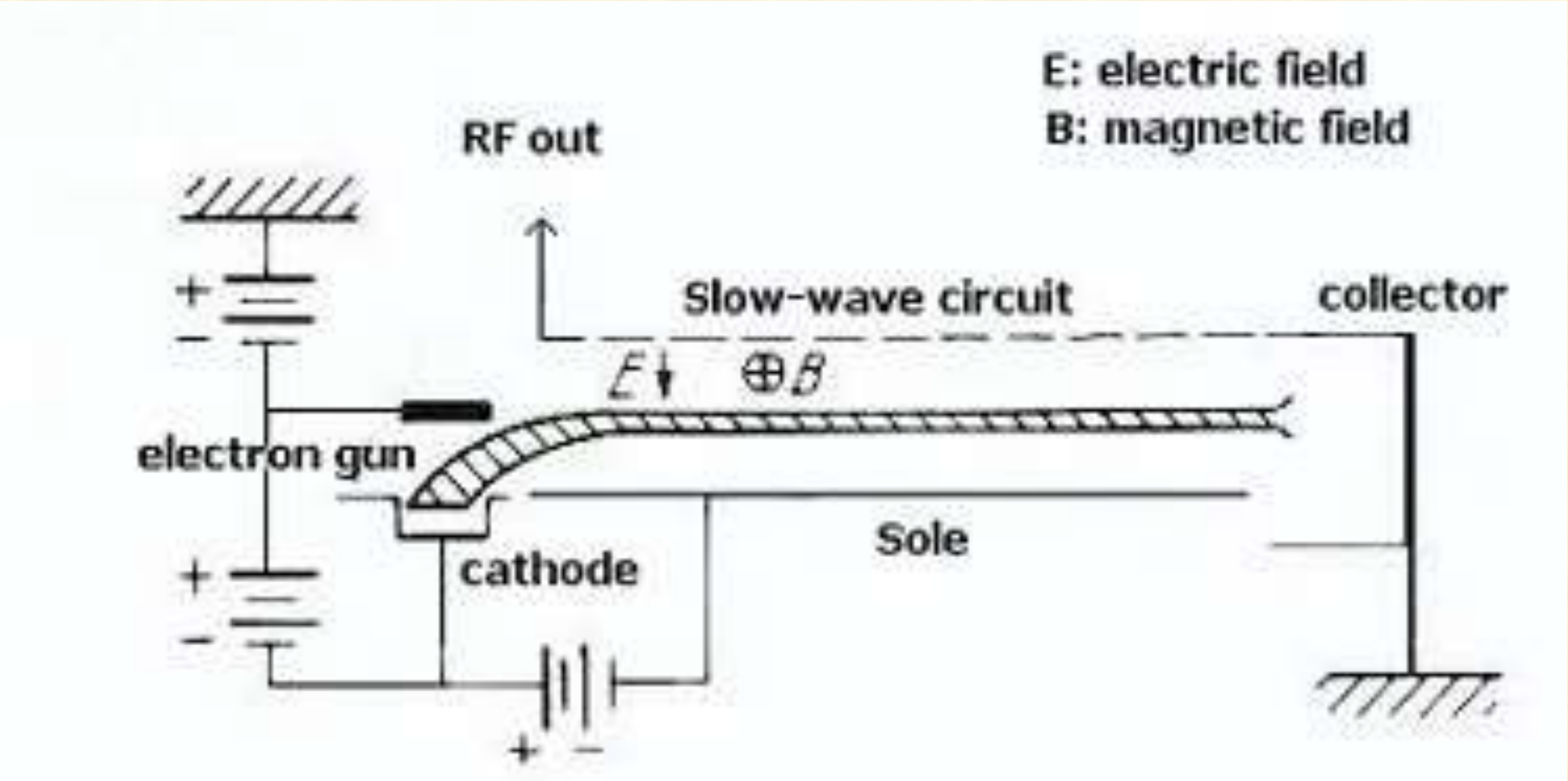
- The electric and magnetic fields in a CFA are perpendicular to each other ("crossed fields"). This is the same type of field interaction used in a magnetron; as a result, the two devices share many characteristics (such as high peak power and efficiency) and they have similar physical appearances. However, a magnetron is an oscillator and a CFA is an amplifier; a CFA's RF circuit (or slow-wave structure) is similar to that in a coupled-cavity TWT.

- Raytheon engineer William C. Brown's work to adapt magnetron principles to create a new broadband amplifier is generally recognized as the first CFA, which he called an **Amplitron**. Other names that are sometimes used by CFA manufacturers include **Platinotron** or **Stabilotron**.

Backward Wave Oscillator (BWO)

- A **backward wave oscillator** (**BWO**), also called **carcinotron** (a trade name for tubes manufactured by CSF, now Thales) or **backward wave tube**, is a vacuum tube that is used to generate microwaves up to the terahertz range. It belongs to the traveling wave tube family. It is an oscillator with a wide electronic tuning range.

- An electron gun generates an electron beam that is interacting with a slow-wave structure. It sustains the oscillations by propagating a traveling wave backwards against the beam. The generated electromagnetic wave power has its group velocity directed oppositely to the direction of motion of the electrons. The output power is coupled out near the electron gun.


E: electric field
B: magnetic field
RF out
Slow-wave circuit
collector
E
B
electron gun
cathode
Sole
+
−
+
−
+ −

Longevity of MW Tubes

- Predictions have been propagating since the 1960s that microwave tubes would have to be displaced by microwave solid-state devices.
- This displacement has occurred only at the low-power and receivin g circuits level of electronic systems.
- Microwave power tubes continue to perform as the only choice for h igh-power transmitters and are expected to maintain this dominant rol e throughout the next generation and beyond.
- Microwave techniques have been increasingly adopted in many ele ctronic systems, such as airborne radar systems, space-borne militar y defense, missile guidance systems, and space communications link s.

Tube Parameters Affecting Performance

- Power vs. Frequency
- Efficiency
- Harmonics
- Intermodulation Distortion
- Gain Flatness, Phase Linearity, and Group Delay
- Noise Figure
- Noise Power Output and Carrier–to–Noise Ratio
- Dynamic Range for Linear Operation

Noise Figure

$$F(dB) = 10 \times \log_{10}\left[\frac{S_i/N_i}{S_0/N_0}\right] = 10 \times \log_{10}\left[\frac{N_a + G_a N_i}{G_a N_i}\right]$$

- Noise figure (F) is the degradation in the signal-to-noise S/N ratio
- S_i and N_i are the input signal and noise levels , S_o and N_o are the output signal and noise levels
- N_a is the noise added by the amplifier and G_a is the gain of the Amplifier
- Since the input noise level is usually thermal nose, the primary source of noise in a TWT/tube is related to the density and electron velocity variations with the electron beam.
- The level of the noise power is related to the number of electrodes in the gun, the size of the electron gun, and its beam optics.

Carrier – to – Noise Ratio

$$\frac{C}{N}(dB \cdot Hz) = P_{out}(dB_m) - \left[174 \, {dB_m}/{Hz} + G_{noise}(dB) + F(dB)\right]$$

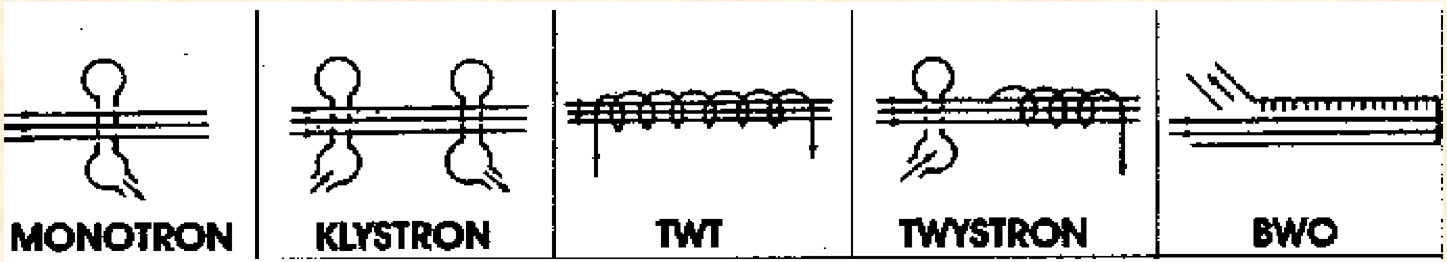
- Ratio of the TWT output carrier at a defined operating point (commonly saturation) and the surrounding TWT noise density.
- C/N is the carrier – to – noise ratio (dB-Hz).
- P_{out} is the single carrier output power in dBm
- F is the TWT noise figure in dB
- G_{noise} is the gain of the noise in the TWT

Conventional Microwave Tubes

Increase of the operating frequency of conventional microwave tubes

RF power output becomes limited due to

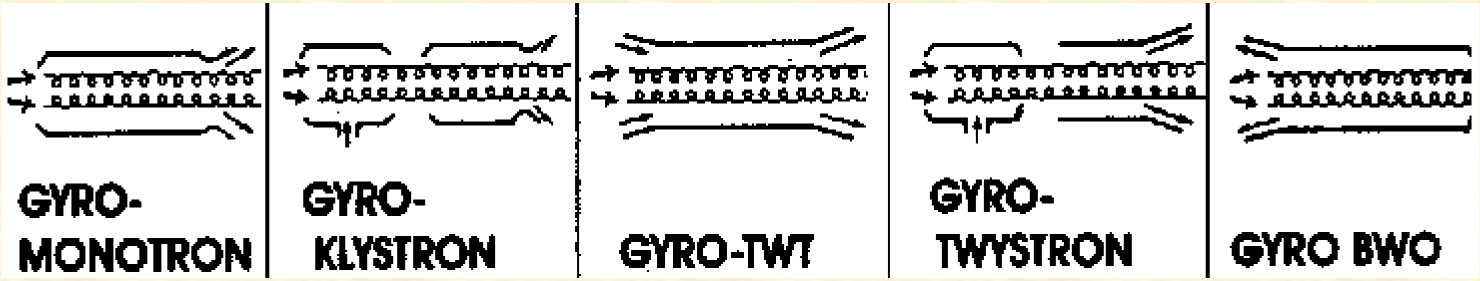
- **— DC power dissipation**
- **— RF losses**
- **— Attainable electron current density**
- **— Heat transfer (restricting the average power capability)**
- **— Material breakdown (arcing) (restricting the peak power capability)**
- **— Difficulty of fabricating tiny parts**



Unconventional high power microwave tubes

operable in the millimetre-wave frequency band

for instance, gyro-devices



Gyro-klystron, application in a linear accelerator

limited bandwidth

cavity-type interaction structures

Gyro-travelling-wave tube (gyro-TWT)

wider bandwidth

propagating waveguide interaction structure

For the communication purpose

there is need to broaden the bandwidth of a gyro-TWT

- **Better measure is transmitter system efficiency = ratio of RF power available from the transmitter to the total power needed to operate the transmitter.**

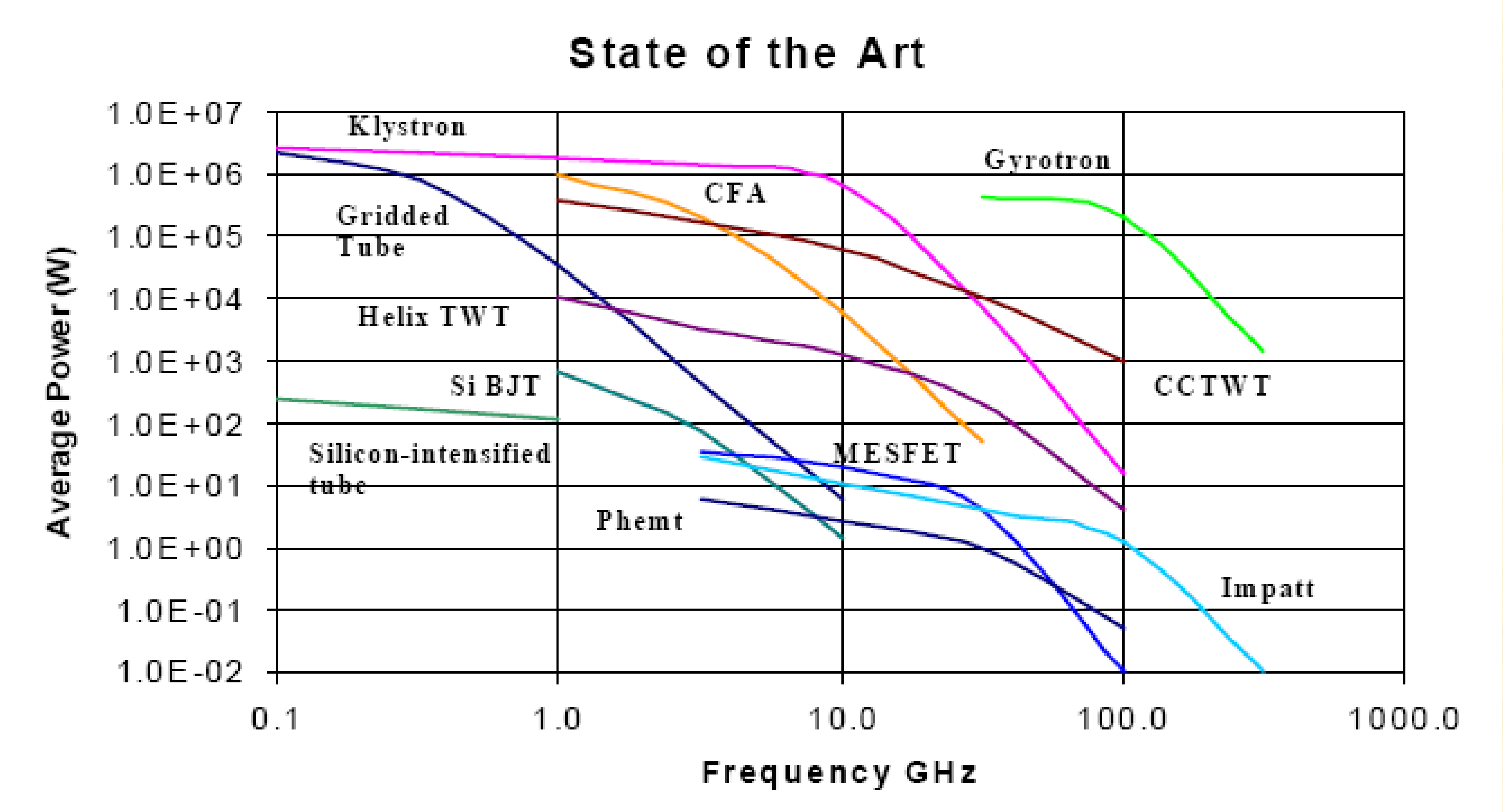
- **The total power includes the power to generate the electrons at the cathode, the power to generate any EM fields required containing the electron beam, the power required to cool the device, any other power needed for the proper operation.**

- **For maximum efficiency most high power RF sources operate saturated (completely On or completely Off with no intermediate levels) – generates rectangular pulse like waveform.**

- **Many times highly shaped transmitted waveforms (amplitude tapered or shaped pulse to reduce time side lobes in pulse compression radars, to minimise RF interference to others) need to be generated – efficiency of tubes is less.**

- **Life time of RF tubes is many tens of thousands of hours. Lack of proper coolants, fans, blowers and damaged of mishandled RF connectors reduce the MTBF of tubes.**

Tube Output Power



Klystrons

- It has high gain and good efficiency
- Capable of higher average and peak power than most othe r tubes.
- Wide bandwidth, long life, low interpulse noise, good stabili ty for doppler processing.

TWT

- ♦ Slightly less power, less gain, less efficiency than Klystron.
- ♦ Wide bandwidth at modest power levels.

Peak Power : up to 30 MW, Average power : 700 KW
Gain : 30 - 70 dB, Efficiency : 15 – 60 %
Bandwidth : 1 – 8 % (Klystron), 15 – 60 % (TWT)

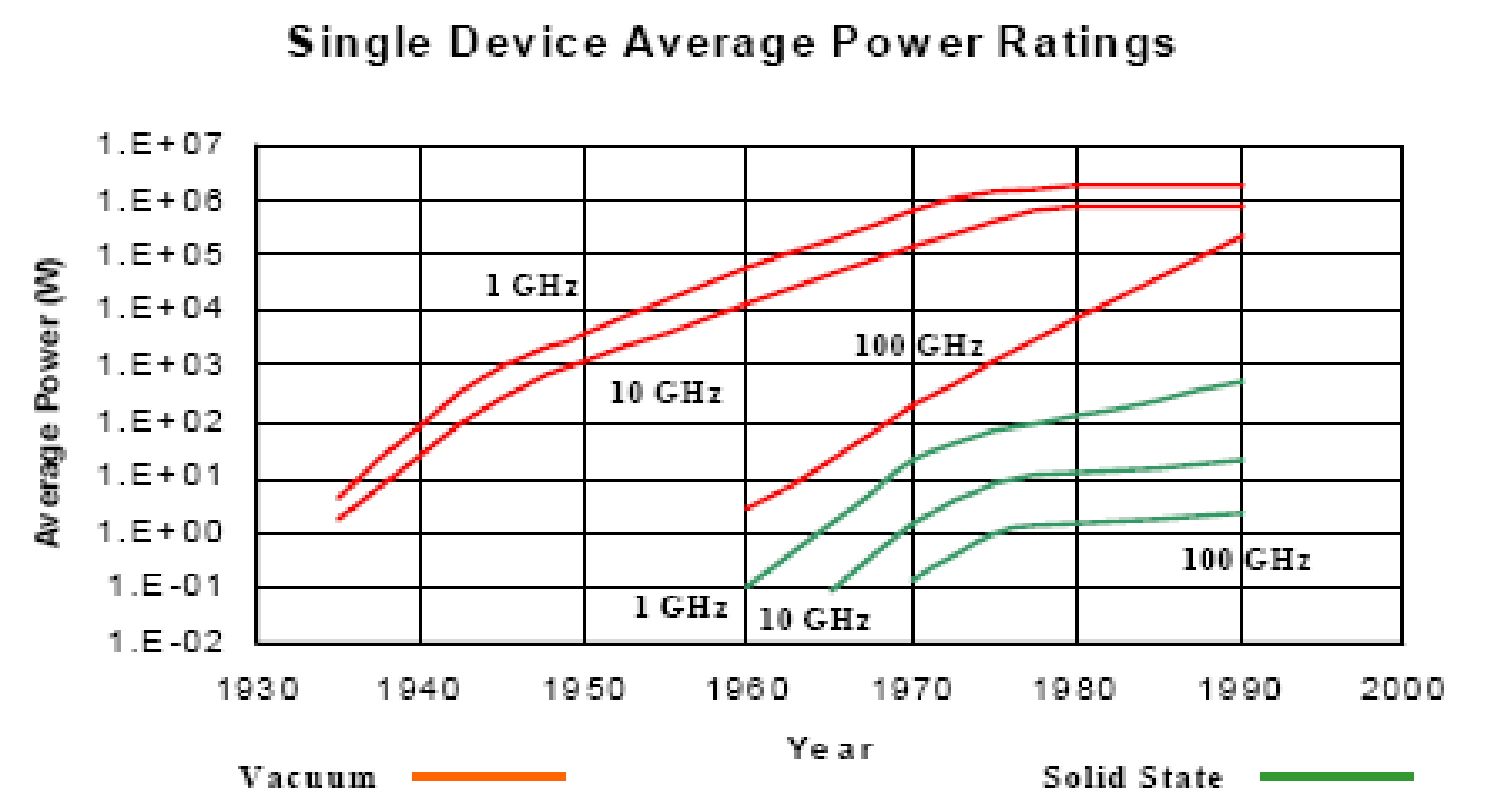
Magnetron

- **It is an oscillator, smaller in size and utilizes lower voltage s**
- **Limited average power, poor noise and stability character istics.**

CFA

- **Capable of high power, good efficiency, wide bandwidth, r elatively low power gain**
- **Generally noisier and less stable than other RF sources.**

TWT/SSPA Output Power Comparison



Solid State Transistor Amplifiers

♦ **Wider Bandwidth, operate at low voltages, ease of maintenance**

♦ **Inherently of low power so that a large number of devices can be combined to generate sufficient high power.**

♦ **For good efficiency they should be operated at high duty cycles.**

The Reality

Vacuum Devices are:

~~Fragile~~	**Robust**
~~Short-lived~~	**Long-lived**
~~Unreliable~~	**Reliable**
~~Inefficient~~	**Efficient**