consists of 8-VSB mod > shoulder corrector > rf converter (0.5 W out) > class A amp > (15 W out) > class AB amp (800 W out) > class AB HPA (25 kW out).

13.2.1 Intermediate power amplifiers (IPAs)

Most IPAs are solid state. The difference between a tube and a solid-state transmitter is mostly in the final amplifier. A tube uses either a triode, tetrode, klystron, diacrode, or an IOT. A solid state is just that; solid-state power amp modules comprise the high-power rf generation stage. It is common to have four 250-W IPA modules to drive a tube final. The transmitter can continue to be used if one of those modules fails, albeit at reduced drive to the final.

The solid-state IPA accepts 5 W of power from the exciter and passes it through three cascaded class A amps before the first class AB amp is encountered. In some systems at the higher UHF frequencies two IPA assemblies are required. The class AB IPA amp feeds four additional class AB final amps in parallel. Class AB allows for a simpler design than class A. Also, there is less heat and power consumption. The four amps are combined in pairs through two circulators, and these are the only components in the IPA which are frequency sensitive. The two resultant signals are then combined in a star point combiner, which creates a 125-W signal out of the IPA (Fig. 13.8).

13.2.2 Power amps

Many transmitters were configured to run final or power amps in parallel. If two amps were used, each would be run at full power and would be combined to produce the full required power. However, a 3-dB loss penalty is generally encountered in the process of combining the two. If one final was lost, the output power is initially at one-fourth power, which could be brought back up to one-half power by reconfiguring the combiner to pass only power from the amp that was still good. No additional power was gained by using two final amps this way, but it is possible to continue at one-half power with one final failed. The NTSC signal would be noisier to fringe viewers but overall coverage would not suffer much. For DTV it is not desirable to run two half-power finals in parallel because of the 3-dB loss encountered when combining them. This reduced power would greatly limit the coverage area as the S/N ratio would drop below the required value (15 dB) at outlying areas. The DTV signal wouldn't degrade; it would simply go away. With DTV it is better to run a full-power main and a full-power backup final. Here one final has the full load, with a standby ready to replace the main if required. Therefore, a main/alternate configuration where there is no combining penalty is advisable, but magic tee doesn't have that high a loss. In addition, amplifiers run more efficiently at full power. They are less efficient if drive to the amplifier is decreased.

The three major power amp technologies for DTV are: IOT, diacrode, and solid state. An IOT transmitter requires more maintenance, coolant replacement every 2 years, cleaning of high-voltage items monthly, and usually quarterly

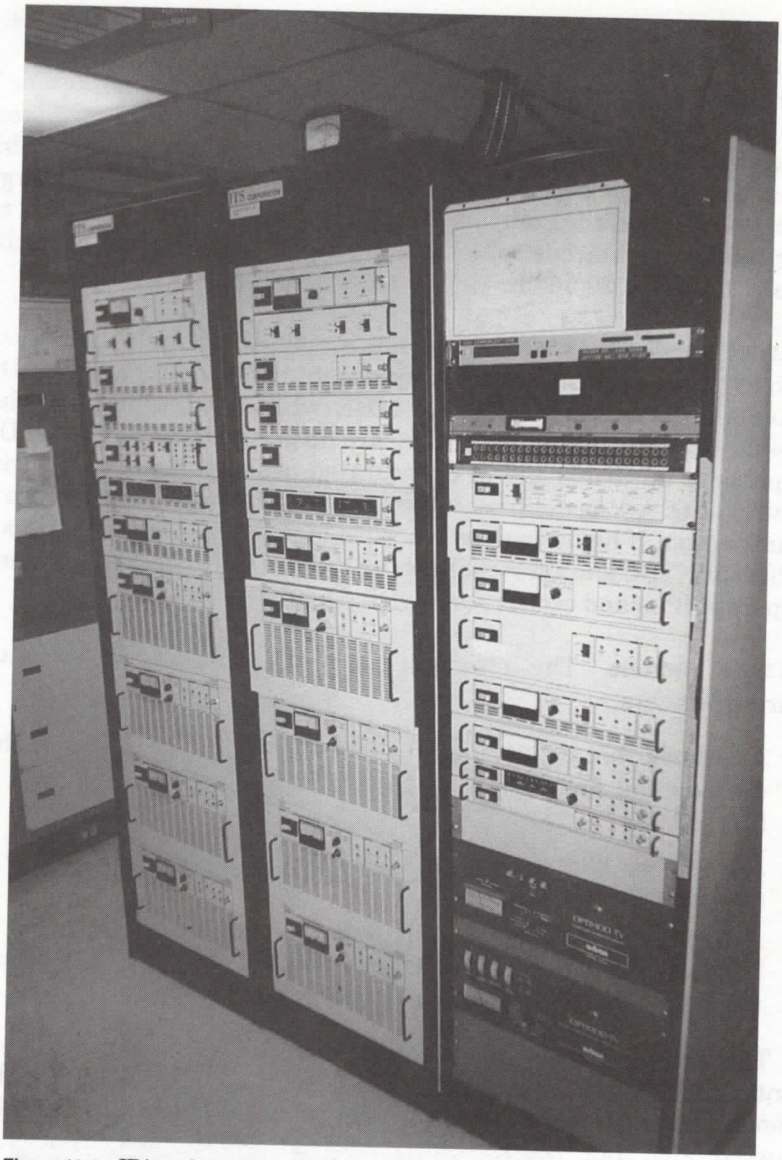


Figure 13.8 IPA replacement for older transmitter. These racks feed the original transmitter final amp.

tuning along with IOT and thyratron replacement. In addition, all the pumps and fans/blowers will require some maintenance effort. Solid-state transmitter maintenance is typically one-tenth that of IOTs. There is no routine tuning. Mainly, routine maintenance consists of air-system maintenance, that is, the replacement of filters. It has been said that solid-state transmitters turn transmitter engineers into filter replacers. However, it should be noted that because of the high currents found in solid-state transmitters, connectors should be inspected regularly.

Historically, klystrons are most likely to be used for high-power UHF NTSC stations, while diacrodes and tetrodes might be used for low-power or staging. The problem with UHF is that the short wavelengths mean things must be smaller, but since high power is needed, things also need to be larger. Tetrodes (and triodes) were initially used for VHF but almost all new VHF transmitters are solid state. Tetrode tube life is 10,000 to 25,000 h, while the diacrode tube life is 12,000 to 20,000 h.

13.2.2.1 Adjacent channels. Currently, only the tetrode and diacrode cavities can be tuned wide enough to accommodate side-by-side channels. Diacrodes can have a 1-dB bandwidth of 14.6 MHz, which means that the channel edges are far enough apart so that there are no group delay problems. Diacrodes are capable of up to 104 kW of unsaturated peak envelope power, giving them a rating of 60-kW peak of sync along with simultaneous provision for 6 kW of aural power. If higher power is needed, diacrodes can be run in parallel. When adjacent NTSC and DTV channels are to be driven through a common diacrode, separate IPAs and exciters are needed for each channel.

13.2.2.2 Tetrode. The *tetrode* is a refinement of the triode. The triode has three elements:

1. A cathode that emits electrons (not counted is the filament that heats the cathode and produces thermionic emission of electrons from the cathode) (Fig. 13.9).
2. A positively charged (with respect to the cathode) plate that receives the electrons.
3. A negatively charged (again with respect to the cathode) control grid between the cathode and plate or anode that controls the amount of electrons that flow between two.

The output of the IPA would be fed to the control grid. The output to the antenna would be connected to the plate. Small currents from the IPA would control large currents from the power amp's power supply. The changing final current and, thus, power would be capacitively coupled out of the transmitter.

A fourth element in the form of another grid was added for the tetrode. This additional grid is called a *screen grid,* and it was added to increase the ability of the tube to amplify without increasing the plate voltage power supply. Some electrons arriving at the plate would essentially bounce off the plate, which would lower the amplification factor of the tube. The screen grid, which was placed between the control grid and plate, prevented that. The screen grid has a positive potential but not as high as the plate's. Its effect was to reduce the interelectrode capacitance between the control grid and the plate. A major advantage of the tetrode plate voltage is that it is generally around 8 kV. This

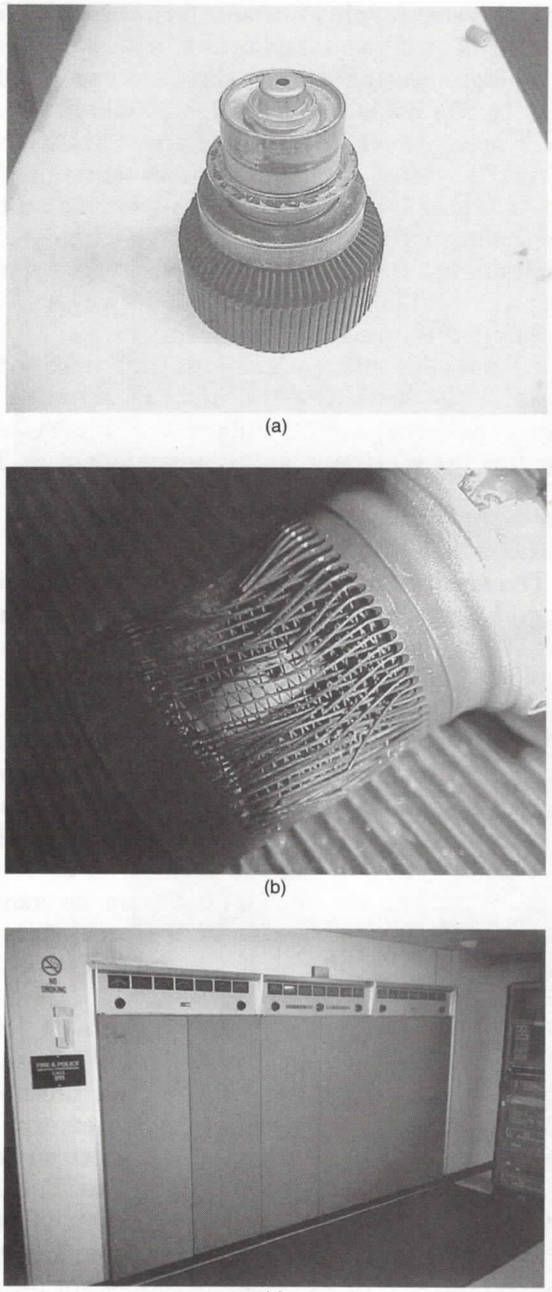


Figure 13.9 (*a*) Low-power triode. (*b*) Cathode and grid of a failed device. (*c*) Vintage 1970s VHF transmitter that used either triodes or tetrodes.

is much lower than the klystron's, plus tetrodes do not require focusing magnets as the klystron does. The efficient removal of heat is the key to making the tetrode practical at high levels. Most tetrodes used in television transmitters are air-cooled. A tetrode's life is about 8000 to 15,000 h.

Tube design for UHF presents conflicting requirements. UHF requires more power for equivalent VHF coverage. As a result, tubes tend to be larger to help dissipate heat. However, higher UHF frequencies call for smaller tubes because of the short wavelengths involved. Tetrodes were used extensively in the low- to medium-power UHF market. These tubes were often used in common-mode amplification of both the visual and aural signals. The linearity of tetrodes is good and, therefore, they can be used in DTV service.

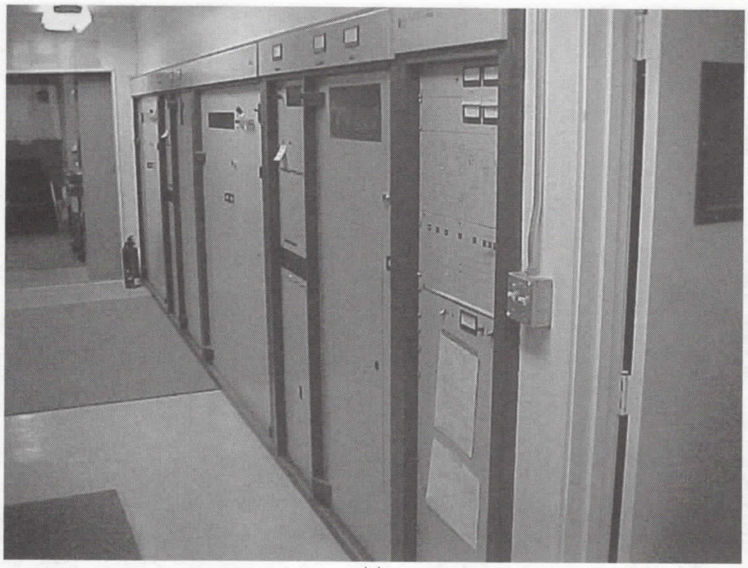
In many tetrodes all the elements are cylindrical or coaxial to each other and connected to pins at the bottom of the unit. This means that current decreases as you travel up each element, while voltage increases. As a result, the center of the tube has the maximum ability to make power. Thus

$$\text{Typical tetrode power} = 8.8\text{ kV} \times 5.5\text{ A} = 30\text{ kW}$$

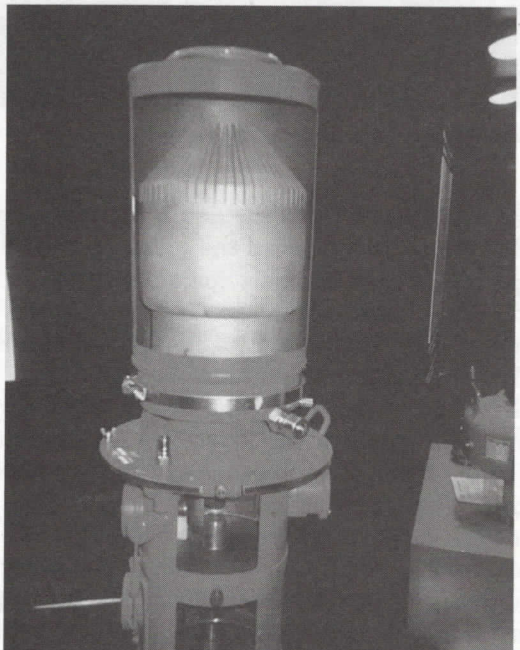
13.2.2.3 Klystrons. The *klystron* is a linear device that overcomes the transit time limitations of a grid-controlled tube by accelerating an electron beam to a high velocity before that beam is modulated (Fig. 13.10). The electron beam modulation is accomplished by varying the velocity of the beam, which causes the drifting of electrons into bunches to produce rf space current. One or more cavities in the klystron reenforce this bunching action at the operating frequency. The klystron's output cavity acts as a transformer to couple the high-impedance beam to a low-impedance transmission line. The spent electrons land on a collector. The collector is generally water-cooled (coolant). A large percentage of a transmitter's wasted heat is carried off as steam from the klystrons. Some actually convert the coolant to steam as moving water to the vapor phase consumes large amounts of heat. The problem is that the heat exchangers at the other end give off equal amounts of heat as the vapor condenses back to water.

The klystron's electron gun and heater usually operate at -15 to -26 kV relative to ground or chassis potential. Electrons emitted from the cathode are accelerated through the rf cavities and drift tubes to the collector, which is at ground potential. The beam is focused by internal and external electromagnetic assemblies (Figs. 13.11 and 13.12). The resultant electron beam is tightly focused, and has uniform density before rf drive is applied. The grid assembly controls the amount of beam current. Sync pulsing schemes usually control this grid to increase beam current during sync pulse time. The grid voltage is generally biased between 0 and -10 kV to set the quiescent beam current. In the klystron rf amplification is accomplished by velocity modulation of the electron beam.

The rf drive is coupled to the beam via the input cavity, which includes a pair of capacitive rings that form a structure called a *gap*. Electrons passing through



(a)



(b)

Figure 13.10 (*a*) Two visual cabinets of a UHF transmitter. (*b*) Klystron with collector exposed.

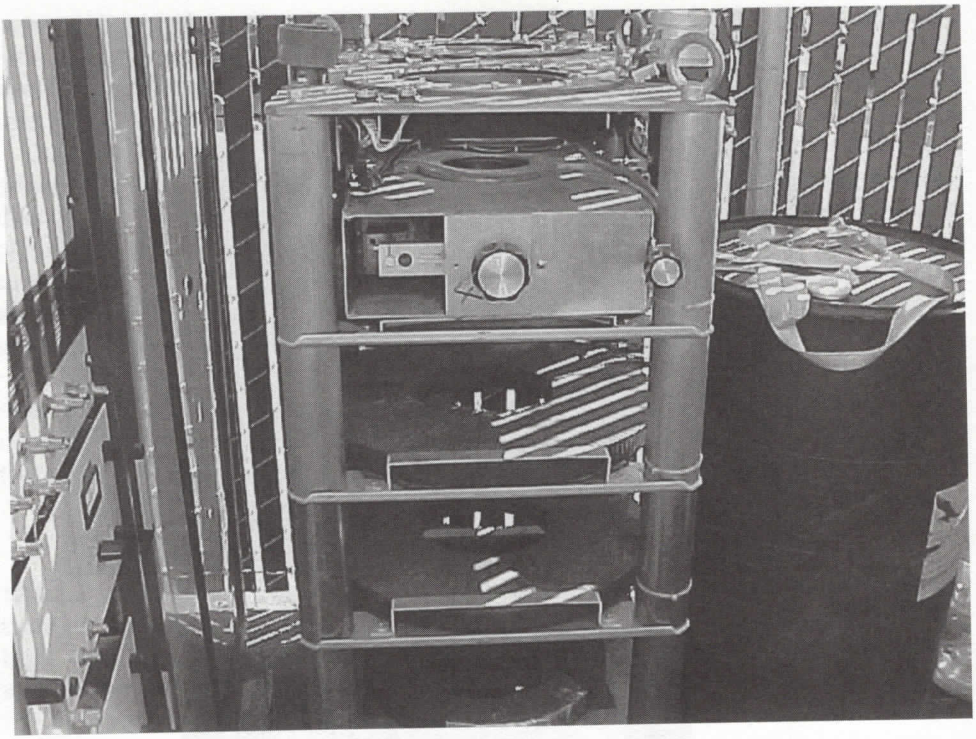


Figure 13.11 External focusing cavity for klystron.

the gap are velocity modulated by the field across the gap. The electrons drift by in what is called a *drift tube* toward the collector. The "bunched" electrons pass additional gaps where they impart some of their energy. These additional gaps are part of additional cavities that are resonant at the desired frequency. The "ringing" that occurs in these cavities further amplifies the bunched electron phenomena. The final gap is the output gap and cavity where rf power is coupled. After the electrons travel past the output gap, they continue on to the collector. It is here that many of the klystron's nonlinearities arise. Electrostatic repulsion of the electrons to each other as they arrive at the collector tends to eliminate bunching at higher rf levels.

The frequency response of a klystron is limited by the impedance/bandwidth product of the cavities, which may be extended by stagger tuning or by the use of multiple resonance filter cavities. Klystron output power ranges up to 60 kW. The klystron has high gain and little external support circuitry. The klystron is a class A device. Tetrodes and diacrodes can be either class A or AB. Since the klystron is a class A device, the average dc input power does not vary significantly with picture content. Typical collector (beam) current is 4 A in a final for visual and 1 A for aural finals. This current is tightly focused by focus coils around the body of the tube. Current that strays from the beam and does not end up in the collector but in the body of the tube is known as "body" cur-

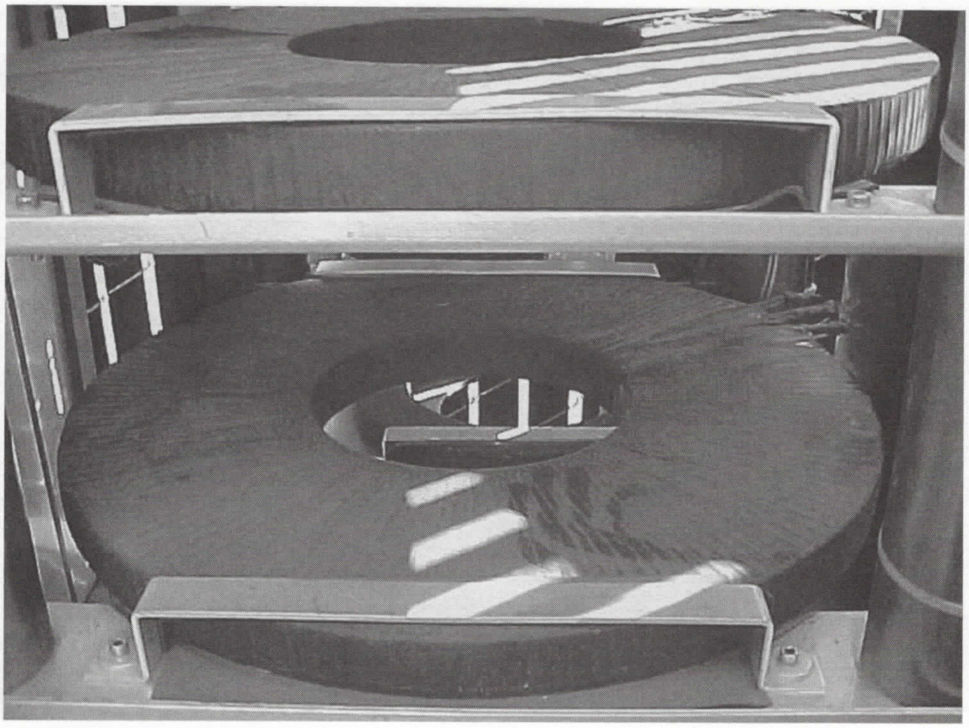


Figure 13.12 Close-up of a focus coil.

rent. High body current is an indication that a tube has a leak and is getting gaseous because electrons in the beam are hitting gas molecules and being scattered. High body current could also mean that the drift tubes are damaged, the cathode is about used up, or the focus coils are misaligned. Typical body currents are under 100 mA. Focus current is generally around 10 A.

A typical klystron transmitter might consume 360 kVA to produce 60 kW of TPO. Common input power would be 480 Vac/3 phase. The high voltage would be 24 kV. Klystron drive from the IPA is usually around 50 μA (Fig. 13.13). Thus

$$\text{Figure of merit (FOM)} = \frac{\text{rf peak power output}}{\text{average dc power input at 50\% APL}}$$

Early klystrons had FOMs of 0.30 to 0.40. With the introduction of modulated-anode pulsing (increased power at NTSC horizontal sync time), FOM increased to above 0.40. The latest generation of external cavity klystrons has achieved FOMs of 0.50, which, when pulsed, may be raised to between 0.60 and 0.70.

Since DTV has unpredictable signal peaks, klystron pulsing is not viable. In addition, since the klystron is operated as a class A device, the beam current has to be biased for full power all the time. However, to stay under the compression

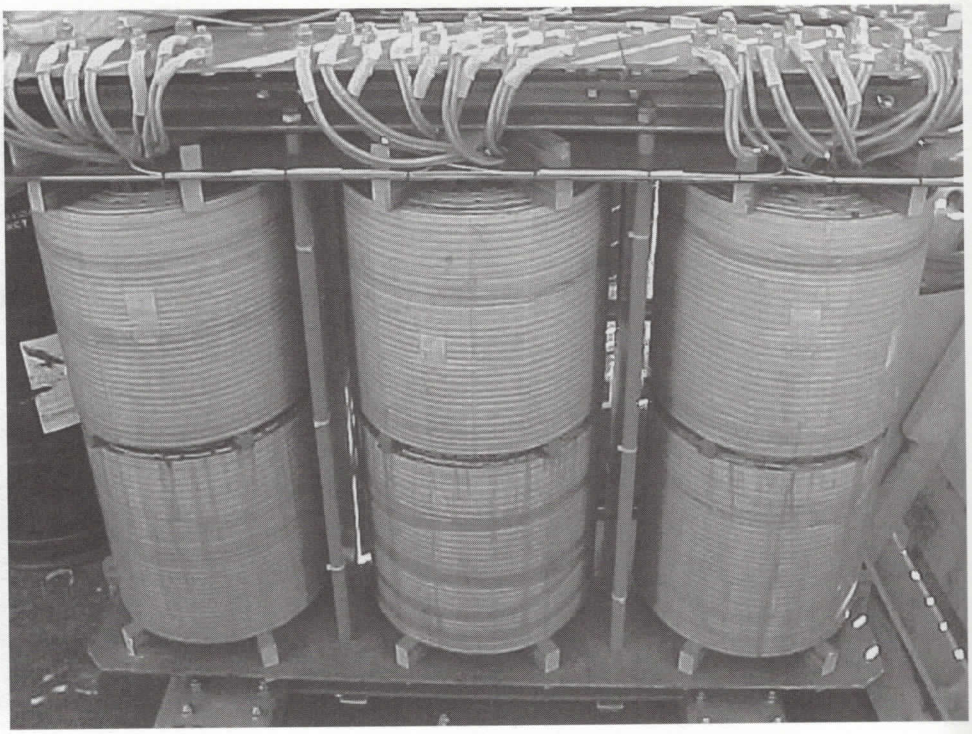
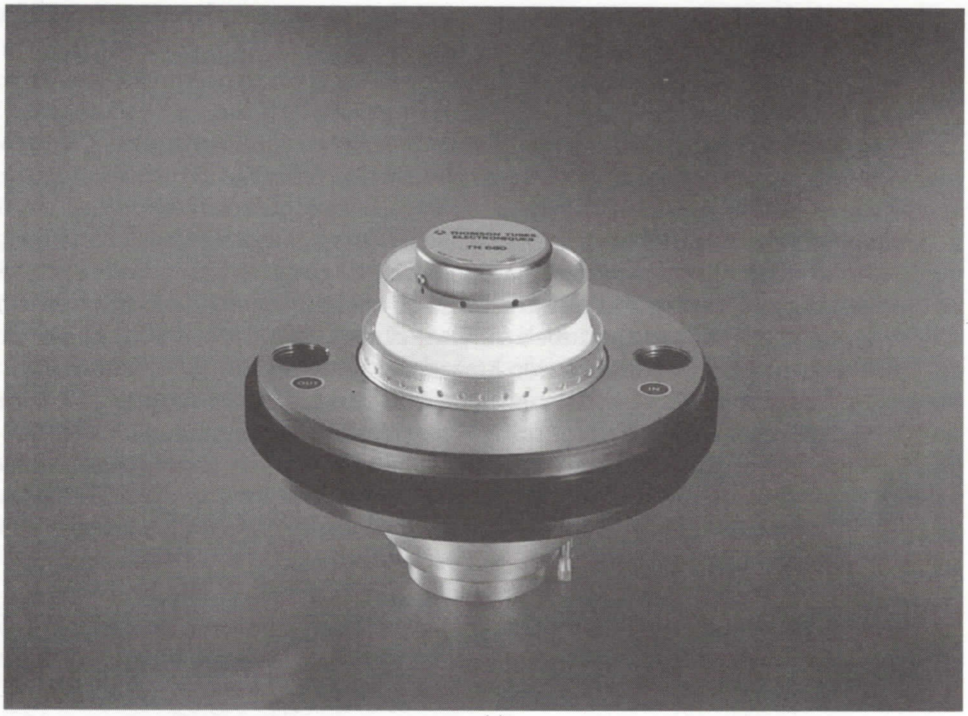


Figure 13.13 Transformers used to create high voltage in a klystron transmitter.

point in the klystron transfer characteristic curve with an extremely small percentage of DTV peaks 7 to 8 dB above average power, the DTV signal drive would have to be backed off. It's conceivable that a 60-kW klystron would only make 5 kW of output power. This is an efficiency of under 10 percent, which makes use of klystrons an expensive option. Another shortfall klystrons have in the DTV realm is bandwidth. DTV requires a wider bandwidth because the data envelope occupies the whole channel, right out to the channel edges. This wider bandwidth requirement would further reduce the klystron's gain. Klystron bandpass is either tilted or bowed, and generally there are no ripples across the bandpass. Any ripples would be from the IPA or before.

Some have proposed that the possibility of modifying existing klystron transmitters to operate the visual klystron's combined visual/aural NTSC service and to operate the aural NTSC amp for DTV service. DTV service can be supported by biasing the aural klystron to the original 20 percent aural beam power, tuning the aural klystron for 6-MHz bandwidth, adding a DTV exciter with the proper predistortion, and adding a masking filter on the DTV section's output.

13.2.2.4 Diacrode. The *diacrode* is a derivative of the tetrode (Fig. 13.14). The diacrode UHF amplification tube was introduced in 1995, and it is basically a



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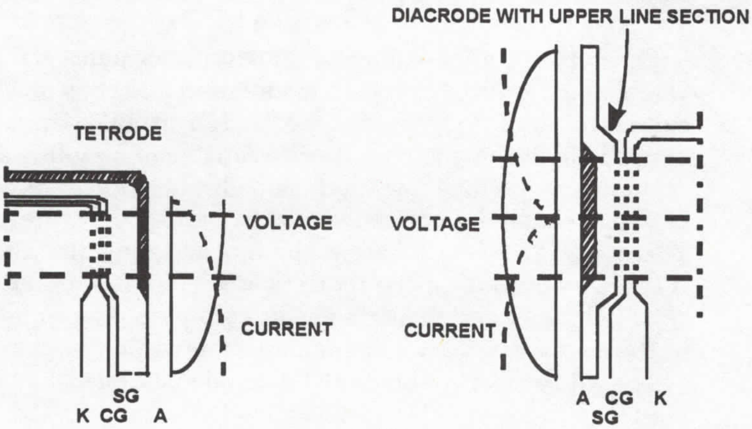


(b)

Figure 13.14 (*a*) High-power 60-kW diacrode (*courtesy of Thomson Tubes Electroniques*). (*b*) The upper shorted quarter-wave line section above the diacrode causes two current maximums instead of the single one in the tetrode.

double-power tetrode. An external cavity is placed on top of the tube and connected across the plate and screen grid. In a diacrode the top of grid G2 is shorted one-quarter wavelength away from the center of the tube. This creates a current null and a peak in voltage one-half the way up the tube, which means that there will be two power peaks, at one-fourth and three-fourths up the tube, instead of one, which is usually found in a normal tetrode. This means power out of a diacrode is double that of a tetrode. While ≈1600 W into a tetrode produces 25 kW out, ≈800 W is needed for the diacrode, a gain of 15 dB. This cavity is actually a two-conductor concentric cylinder, that is, in effect, a one-quarter wavelength-shorted transmission line measured from the top of the cavity to the tube's vertical center. Its purpose is to reflect an open circuit into the vertical center horizontal plane of the tube. The result is that the rf current between the cathode and the plate in this plane is nearly zero. This creates two horizontal planes of maximum current flow, one at the base of the tube and one above the tube at the cavity short circuit. The diacrode uses the same plate voltage as a basic tetrode. In the diacrode the anode current and the rf power output capability are effectively doubled over that provided by the basic tetrode.

In a ground grid-amp design an rf drive of 800 W is applied between the cathode and ground. The rf output power is then available between the plate and ground. The diacrode uses a plate voltage of 8500 V, which is about the same as a conventional tetrode. A diacrode rated at 25-kW DTV average power is approximately 7 in tall and 8 in in diameter, it weighs 14.3 lb, and it is water-cooled. Lower-power diacrodes are air-cooled. Diacrodes cost about $26,500, and have a life of +20,000 h.

These tubes offer sufficient linear performance for amplifying combined visual and aural signals. Intermodulation and cross-modulation correction circuits are used to prevent one carrier from contaminating another. The diacrode is the only current device capable of handling adjacent channel operation because it has low-input impedance, which eliminates the need for an external channel combiner. It still requires separate paths up to the final. There are 128 $N + 1$ adjacent channel assignments. The ratio of DTV peak to NTSC power must be one-tenth to one-fortieth. If other technologies are used, $N + 1$ channel assignments need two separate antennas because of intermod in the combiner. $N - 1$ assignments can use one combiner and one antenna.

Several items have made the diacrode possible:

Hypervaportron cooling, that is, the vapor state right at the tube surface.

The vapor into the tube is around 15°C above ambient at 18 gal/min.

Some of the cooling water goes through a filter to remove impurities.

If the impurities get too high (≈100 kΩ), the water becomes too conductive. It will carry too much heat away, and the transmitter will shut down.

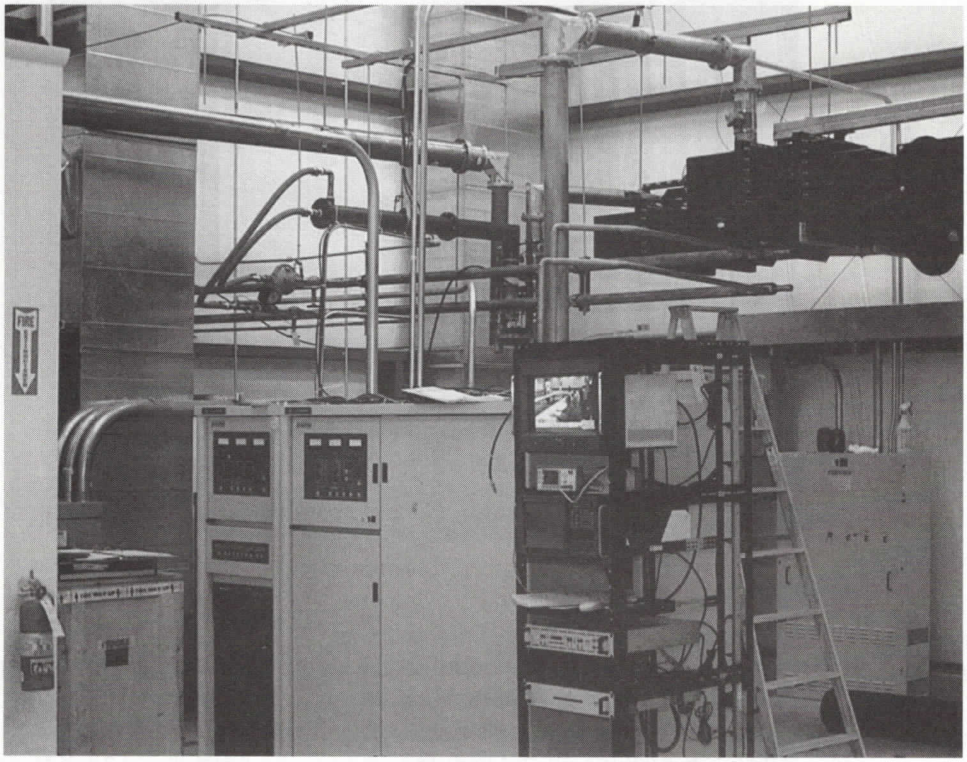
Pyrolytic graphic grids, which have a zero temperature coefficient of expansion. They stay extremely elastic, even at high temperatures.

Improved ceramic to metal bonding.

Improved cathode emissivity for high power.

13.2.2.5 Induction output tube (IOT). The IOT is a variant of the klystron (Figs. 13.15 and 13.16). While the klystron modulates the velocity of the electron beam, the IOT modulates the density of the beam as the grid of a tetrode would. The advantage of an IOT over a conventional klystron is the same as a tetrode has over a klystron—high efficiency without the need for a long electron beam drift space. However, the IOT also has the same advantage as the klystron has over the tetrode—electron beam collection takes place with a collector and not at a plate, which is part of the rf circuitry, as in a tetrode. The IOT uses a high beam-supply voltage to reduce beam current, which increases the efficiency of the tube. Power is extracted from the IOT in the same manner as a klystron.

The IOT comes in multiple sizes. Average power out of the devices ranges from 9.2 to 23 kW. IOTs have beam supplies that range from 25 to 35 kV. The



(a)

Figure 13.15 (*a*) IOT transmitters. Transmitter on left has DTV channel mask above it. (*b*) Close-up of transmitter.