CHAPTER 4
TRANSMITTERS

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4.1 INTRODUCTION

The Transmitter as Part of a Pulsed Radar System. Figure 4.1 shows a block diagram of a typical pulsed radar system. Of these dozen blocks, the public news media generally show only the antenna and displays. The rest of the blocks are "unsung heroes," but they are equally important to the system and can be equally interesting from a design standpoint.

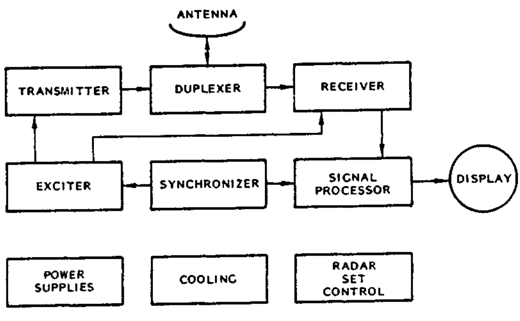

FIG. 4.1 Block diagram of a typical radar system.

The transmitter is usually a large fraction of radar system cost, size, weight, and design effort, and it typically requires a major share of system prime power and maintenance. It generally ends up being a big box that sits in the corner of the radar equipment room, hums to itself, and has a big sign on it that says, "Danger, High Voltage"; so most people prefer to keep away from it. Its insides tend to look peculiar, more like a brewery than a TV set or a computer. This chapter will try to explain why transmitters have to be what they are and hopefully will make them appear a little less peculiar to the reader.

Why So Much Power? Transmitters are big, heavy, and costly and draw so much prime power because they are required to generate so much RF power output; and that requirement, in turn, comes from the radar system design tradeoffs.

The useful range of a search radar varies as the fourth root of the product of average RF power, antenna aperture area (which determines antenna gain), and the time allowed to scan the required solid angle of coverage (which limits how long the signal in each direction can be collected and integrated to improve signal-to-noise ratio):

$$R^4 \propto P \times A \times T \tag{4.1}$$

The range varies as the fourth root of power because both the outgoing transmitted power density and the returning echo energy density from the target become diluted as the square of the distance traveled. Trying to increase range by increasing transmitter power is costly: a 16-fold increase in power is needed to double the range. Conversely, negotiating a reduced range requirement can produce remarkable savings in system cost.

Power-aperture product as a measure of radar performance is fundamental. It is so fundamental that it was explicitly mentioned in the SALT-I Treaty as the basis for limiting the capabilities of antiballistic missile (ABM) radars.

Receiver sensitivity is not shown as a factor in Eq. (4.1) because thermal noise sets a definite limit on receiver sensitivity, and this simplified range equation merely assumes that the receiver is always made as sensitive as possible.

Since average transmitter power is only one of the factors in the range equation and is so costly, why does power usually end up being so high? Wouldn't it be better to use less power and to make up for it with more aperture or more scan time? The flaw in this argument is that increasing the antenna aperture increases its cost quickly because its weight, structural complexity, dimensional tolerance problems, and pedestal requirements grow rapidly with antenna size. The only other factor, scan time, is usually set by some definite system operational requirement: to look at all aircraft within 100 mi every 4 s, for example, to permit prompt recognition of changes in aircraft direction of travel; so scan time is usually not flexible (which probably explains why everyone talks about the "power-aperture product" of a radar rather than its "power-aperture–scan-time product").

It obviously would not make sense for a radar to have a huge, costly antenna and a tiny, inexpensive transmitter, or vice versa, because doubling the tiny part would allow cutting the huge part in half, which would clearly reduce total system cost. Thus, minimizing total system cost requires a reasonable *balance* between the costs of these two subsystems. The result, for any nontrivial radar task, is that significant transmitter power is always demanded by the system designers.

The same result occurs when the system design is based on a required range coverage in the presence of standoff jammers (rather than just thermal noise).

For detection of a target carrying a self-screening jammer, the range equation becomes

$$R^2 \propto (P_r \times A_r) / (P_j \times A_j) \tag{4.2}$$

where P_r and A_r are the power and aperture of the radar and P_j and A_j are those of the jammer. The result is very similar: power and aperture are still the driving factors, and a balanced system design again results in significant transmitter power.

The inescapable conclusion is that "It's watts up front that count." The desire to attain maximum radar performance capability thus means, more often than not, that *both* the antenna size and the transmitter power are pushed to the maximum affordable.

Pushing the transmitter design to the maximum affordable power is not without its problems, however. Historically, this pressure has often led to problems in development time, unexpected costs, and other risks, especially when a new RF tube had to be developed for the application. The AN/FPN-10 L-band beacon radar system development, for example, was never completed because the tube vendor was unable to make the magnetron stable enough over the wide range of duty cycle. The ballistic missile early-warning system (BMEWS) radar development was in similar danger until a second (backup) tube development contract was placed that used integral vacuum cavities rather than external cavities for the high-average-power klystron development.[1] Even a "successful" RF tube development may end up with a design that is marginal in arcing rate and/or in cooling design, leading to reliability problems, excessive maintenance and logistics costs, and an unhappy customer.

As a result of the risks of pushing RF tube developments to (or unwittingly beyond) the state of the art, and especially if the desired power is known to be beyond the capabilities of a single tube, it becomes attractive to use more than a single RF tube and to combine their RF outputs; this turns out to be a very practical approach, as will be discussed later (Sec. 4.5). This ability to combine, readily and reliably, is also what makes solid-state transmitters practical, since individual solid-state RF devices have much lower power-handling capability than single RF tubes. Combining a few RF tubes to obtain a needed high-power level adds complexity to a transmitter, of course; but, on the other hand, combining a *large* number of RF devices, as must typically be done for solid-state transmitters, leads to certain advantages, such as graceful degradation and improved reliability, as described in Chap. 5.

Why Pulsed? Radar transmitters would be much less complex and costly if they could simply operate CW (continuous-wave) like broadcast stations. Having to generate very high pulsed RF power leads to much higher operating voltages (both dc and RF), energy storage problems, and the necessity for high-power switching devices. Some RF devices, like Class C amplifiers (tube or solid-state), are *self-pulsing* and draw current only when RF drive is applied, but most microwave tubes require some type of pulse modulator (Sec. 4.8) so they won't waste power and so they won't generate interfering noise during the receiving period between pulses.

Basically, pulsing is used because it's hard to hear while you're talking (not everyone at meetings seems to understand that point). In a radar system, if the transmitter is always on, it is very hard to keep the transmitter from interfering with the receiver that is trying to hear faint echoes from distant targets. CW radars have been made to work by using separate transmit and receive antennas to isolate the receiver from the transmitter. When the two antennas cannot be widely enough separated to reduce transmitter leakage into the receiver below the receiver noise level (such as when both antennas have to be on the same vehicle), the residual transmitter leakage can be reduced by *feedthrough nulling*, which works by using negative feedback at the receiver input to cancel whatever transmitter carrier signal may appear there. The feedback loop must be selective enough, however, to cancel only the carrier, since signals offset from the carrier include the desired target doppler signals. As a result, a fundamental limitation in CW radar system sensitivity is that leakage into the receiver of transmitter noise sidebands (resulting from imperfect transmitter stability) sets a limit below which small moving-target signals cannot be seen; the maximum range capability of CW radars is often limited by this factor.

A pure CW radar system can detect moving targets by their doppler offset, but no range information is obtained. The normal solution to that problem is to use an FM–CW system, in which the transmitted frequency is swept (usually linearly versus time) so that both range and doppler information can be extracted by proper interpretation of the received signals;[2] the frequency of the echo determines how long ago the signal was transmitted and thus the range to the target. Nevertheless, one fundamental limitation in such CW radars is that weak echoes from distant targets must compete with strong echoes from short-range clutter. This requires superb clutter cancellation, which in turn is limited by transmitter instabilities (which produce noise sidebands). In other words, strong short-range clutter effectively adds more transmitter leakage into the receiver.

In pulsed radar systems, short-range and long-range echoes arrive at different times, and receiver sensitivity can be adjusted accordingly with STC (sensitivity time control). Note that high-PRF pulse doppler systems, which also receive signals from multiple ranges simultaneously, suffer the same type of limitation as CW radars, so long-range pulse radars seldom use a continuous pulse doppler waveform. However, much of the same benefit of wide unambiguous doppler coverage can be obtained by a compromise waveform called *burst*, in which a finite group of high-PRF pulses is transmitted; the duration of the burst is made short enough to avoid making long-range target echoes compete with short-range clutter echoes.

A further disadvantage of CW radar is that it requires two antennas, which effectively "wastes" 3 dB of range-equation performance that could be gained if that total aperture area were combined into a single antenna and used for both transmit and receive. Pulsed radar does exactly that; it shares a single antenna for both the transmitter and the receiver by using a *duplexer*,[2] as shown in Fig. 4.2.

A gas-tube duplexer (Fig. 4.2*a*) uses the presence of high power during transmit to fire the gas-filled T/R (transmit/receive) "tubes," which are actually just sections of transmission line filled with a low-breakdown-voltage gas, to direct the transmitter power to the antenna. The T/R tubes recover (deionize) quickly after the transmitted pulse, which then allows received signals to flow to the receiver. A limiter is also used, as shown, to pro-

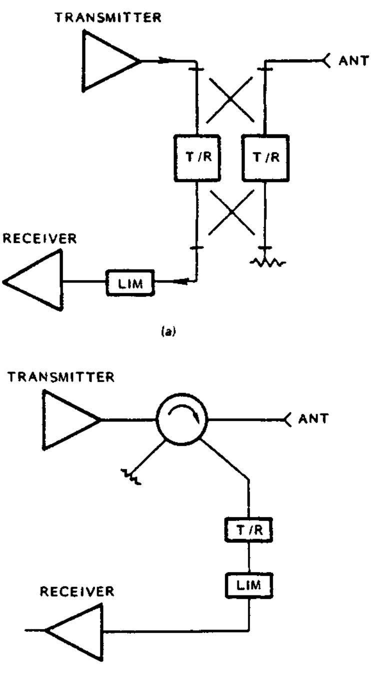

FIG. 4.2 Duplexers. (*a*) Gas-tube duplexer. (*b*) Ferrite circulator duplexer.

tect the receiver from power leakage through the T/R tubes during transmit. The limiter also protects the receiver from signals from nearby radars that may not be strong enough to fire the T/R tubes but could be large enough to hurt the receiver.

A ferrite duplexer (Fig. 4.2*b*) uses a ferrite circulator,[3] instead of T/R tubes, to send the transmitter power to the antenna and the received signals to the receiver. However, in this case reflected power from the antenna voltage–standing-wave ratio (VSWR) during transmit also is directed to the receiver, so a T/R tube and limiter are still required to protect the receiver during transmit.

In either case, the duplexer accomplishes the objective of letting the transmitter and the receiver share a single antenna in pulsed radar systems.

4.2 MAGNETRON TRANSMITTERS

Historically, the invention of the microwave magnetron during World War II made pulsed radar practical, and early radar systems were undoubtedly tailored around what magnetrons could do. The 5J26, for example, has been used in search radars for over 40 years. It operates at L band and is mechanically tunable from 1250 to 1350 MHz. It is typically operated at 500-kW peak power with 1-μs pulse duration and 1000 pulses per second (pps), or 2 μs and 500 pps, either of which is 0.001 duty cycle and provides 500 W of average RF power. Its 40 percent efficiency is typical for magnetrons. The 1- to 2-μs pulse duration provides 150- to 300-m range resolution and is "convenient" for magnetrons, which simply oscillate at the resonant frequency of their mechanical cavities and are subject to frequency instabilities that would be unacceptable compared with the narrower signal bandwidth of longer pulse widths.

Magnetron transmitters are well described in the literature.[2] They readily produce high peak power; and they are quite small, simple, and low in cost. Pulsed magnetrons vary from a 1-in^3, 1-kW peak-power beacon magnetron up to several megawatts peak and several kW average power, and CW magnetrons have been made up to 25 kW for industrial heating. All commercial marine radars have used magnetrons.

Magnetron transmitters have been widely used for moving-target indication (MTI) operation, typically allowing 30 to 40 dB of clutter cancellation. It is remarkable that magnetrons are stable enough for MTI operation at all, considering that it requires the self-excited magnetron to repeat its frequency, pulse to pulse, within about 0.00002 percent. The starting RF phase, however, is arbitrary on each pulse as the magnetron starts to oscillate, so a locked coho (coherent oscillator)[4] or an equivalent (which measures phase on transmit and corrects in a signal processor on receive) must always be used. The high-voltage power supply (HVPS) and pulse modulator must provide very stable (repeatable) pulsing to the magnetron, as well, in order not to spoil MTI performance. Modulation of magnetron frequency by microphonics, from ambient vibration, has also been a limiting factor in some cases.

Automatic frequency control (AFC) is typically used to keep the receiver tuned to the transmitter as the magnetron slowly drifts with ambient temperature and self-heating. The AFC can be applied to the magnetron instead to keep it operating on an assigned frequency, within the accuracy limits of its tuning mechanism.

Limitations. In spite of their wide capabilities, magnetrons may not be suitable for various reasons:

1. If precise frequency control is needed, better than can be achieved through the magnetron tuner after allowing for backlash, warmup drift, pushing, pulling, etc.

2. If precise frequency jumping is required, or frequency jumping within a pulse or within a pulse group.

3. If the best possible stability is required. Magnetrons are not stable enough to be suitable for very long pulses (e.g., 100 μs), and starting jitter limits their use at very short pulses (e.g., 0.1 μs), especially at high power and lower frequency bands.

4. If coherence is required from pulse to pulse for second-time-around clutter cancellation, etc. Injection locking has been tried but requires too much power to be attractive. For the same reason, combining the power outputs of magnetrons has not been attractive.

5. If coded or shaped pulses are required. A range of only a few decibels of pulse shaping is feasible with a magnetron, and even then frequency pushing may prevent obtaining the desired benefits.

6. If lowest possible spurious power levels are required. Magnetrons cannot provide a very pure spectrum but instead produce considerable electromagnetic interference (EMI) across a bandwidth much wider than their signal bandwidth (coaxial magnetrons are somewhat better in this respect).

Magnetron Features. Where a magnetron is suitable, it can be obtained with features that have broadened considerably since its early days.

Tuners. High-power magnetrons can be mechanically tuned over a 5 to 10 percent frequency range routinely, and in some cases as much as 25 percent.

Rotary Tuning. The rotary-tuned ("spin-tuned") magnetron was developed around 1960.[5,6] A slotted disk is suspended above the anode cavities as shown in Fig. 4.3 and, when rotated, alternately provides inductive and capacitive loading of the cavities to raise and lower the frequency. Very fast tuning rates are feasible because each revolution of the tuner disk tunes the tube across the band and back a number of times equal to the number of cavities around the anode. The disk is mounted on bearings inside the vacuum (developed first for rotating-anode x-ray tubes) and is magnetically coupled to a shaft outside the vacuum. At 1800 r/min, a tube with 10 cavities tunes across the band 300 times per second. By ensuring that the modulator pulse rate is not synchronous with the tuning rate, the transmitted frequency will vary from pulse to pulse in a regular pattern as the PRF beats with the tuning rate. Irregular (pseudorandom) jumping of the frequency can be obtained by varying the modulator PRF or by varying the motor speed rapidly. First-order tracking information for the receiver local oscillator (LO) is obtained from an

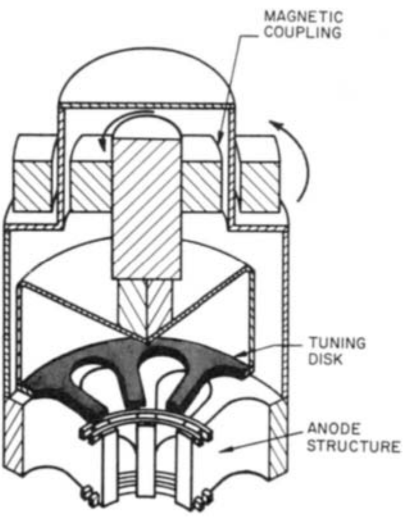

FIG. 4.3 Magnetron rotary tuner. (*Courtesy of Raytheon Company.*)

internal transducer, usually capacitive, on the same shaft as the tuning disk.

The use of rotary tuners involves some penalties besides higher cost and weight. Less average power output is feasible than for tubes with conventional tuners, since cooling the rotary tuner is more difficult. Precise band-edge tuning is not assured; since the entire tuning range is always covered on each cycle and since system operation outside the assigned band is usually not permissible, tolerances on tuning range must be absorbed within the band. When used for MTI (with the tuner stopped), stability is less good than with other tuners.

Stabilized Magnetrons. The most common form of stabilized magnetron is the coaxial magnetron, in which a high-Q annular cavity is intimately coupled to the anode vanes inside the inner cylinder, as shown in Fig. 4.4. At the higher frequencies (above X band) an inside-out version, called an inverted coaxial magnetron, as shown in Fig. 4.5, is more suitable because the cavity becomes very small and the normal construction would leave inadequate room for the cathode and the anode structure.

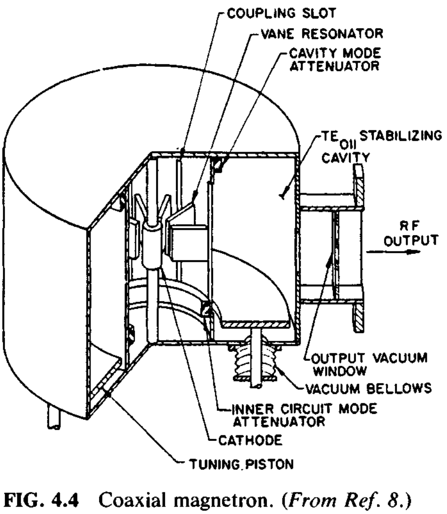

FIG. 4.4 Coaxial magnetron. (*From Ref. 8.*)

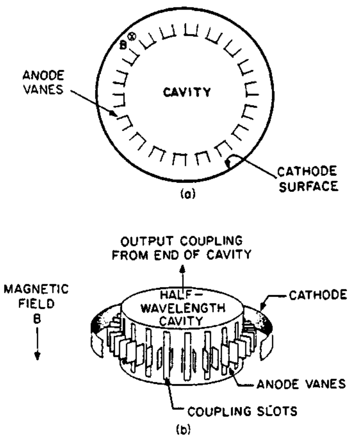

FIG. 4.5 Inverted coaxial magnetron. (*a*) Simplified cross section. (*b*) Simplified perspective.

These techniques[5,7,8] permit an increase in stability by a factor of 3 to 10 in pushing figure and pulling figure (defined later in this section). This is of most importance at high frequency (X and K bands), where the effects of pushing and pulling are more significant compared with the bandwidth occupied by typical system pulse widths. Stabilization is also most practical at these frequencies because a high-Q cavity is then of acceptable size. MTI performance may be improved over conventional magnetrons because the pulse-to-pulse and intrapulse frequency stability is better. However, the expected benefit may not be realizable unless jitter and noise during the starting time of each pulse are low enough, and these characteristics vary considerably among the different types of stabilized magnetrons.

Common Problems. The classic problems of magnetron operation still exist, but they now tend to be better understood, specified, and controlled. Briefly, the most common problems are as follows:

1. *Sparking:* Especially when a magnetron is first started, it is normal for anode-to-cathode arcing to occur on a small percentage of the pulses. Sometimes this also applies to moding and/or misfiring. The modulator must tolerate this for brief periods without tripping off and must deliver normal output immediately following sparking.

2. *Moding:* If other possible operating-mode conditions exist too close to the normal-mode current level, stable operation is difficult to achieve. Starting in the proper mode requires the proper rate of rise of magnetron cathode voltage, within limits that depend on the tube starting time and the closeness of other modes. Too fast a rate of rise may even result in failure to start at all. Since starting time is roughly $4Q_L/f_o$, where Q_L is the loaded Q, it is more difficult and inefficient to operate high-power, low-frequency magnetrons at short pulse lengths. Techniques to minimize this problem include *despiking*, usually a simple series-*RC* network to slow down the modulator voltage rate of rise, or a *pulse bender*, which uses a diode and a parallel-*RC* network to load down only the last portion of the rate of rise.[9] On the other hand, too slow a voltage rate of rise (or too slow a fall time at the end of the pulse) can also excite a lower-current mode if that tube has one.[10]

3. *Noise rings:* Excessive inverse voltage following the pulse, or even a small forward "postpulse" of voltage applied to the magnetron, may make it produce sufficient noise to interfere with short-range target echoes. The term *noise ring* is used because this noise occurs at a constant delay after the transmitted pulse and produces a circle on a plan position indicator (PPI). This can also occur if the pulse voltage on the magnetron does not fall fast enough after the pulse.[11]

4. *Spurious RF output:* In addition to their desired output power, magnetrons generate significant amounts of spurious noise. The kinds and amounts are similar to those listed under crossed-field amplifiers (CFAs) in Table 4.2 below and discussed in Secs. 4.3 and 4.4, but the resonant nature of the magnetron tends to suppress noise that is far from the operating frequency, except for harmonics.

5. *RF leakage out of the cathode stem:* Typically, an S-band tube may radiate significant VHF and UHF energy as well as fundamental and harmonics out of its cathode stem. This effect varies greatly among different magnetrons, and when it occurs, it also varies greatly with lead arrangements, filament voltage, magnetic field, etc. Although it is preferable to eliminate cathode-stem leakage within the tube, it has sometimes been successfully trapped, absorbed, or tolerated outside the tube.

6. *Drift:* Magnetron frequency varies with ambient temperature (of the cooling air or water) according to the temperature coefficient of its cavities, and it may also vary significantly during warmup. Even during continuous operation, a change in tuner setting may result in drifting again after the change if cavity or tuner heating varies with tuner setting. Temperature-compensated designs are available in some cases.

7. *Pushing:* The amount by which a magnetron's frequency varies with changes in anode current is called its *pushing figure*,[10] and the resulting pulse-to-pulse and intrapulse frequency changes must be kept within system requirements by proper modulator design.

8. *Pulling:* The amount by which a magnetron's frequency varies as the phase of a mismatched load is varied is called its *pulling figure*.[10] Thanks to the ready availability of ferrite isolators, pulling is seldom a problem in modern radar

transmitters. For the same reason, long-line effect[12] is a problem of the past, since isolators readily reduce the mismatch seen by the magnetron to a value low enough to guarantee freedom from frequency skipping.

9. *Life:* Although some magnetrons have short wear-out life, many others have short life because of mishandling by inexperienced personnel. Dramatic increases in average life have been obtained by improved handling procedures and proper operator training (Sec. 4.4).[13,14]

10. *Tuner life:* Because of cost and size tradeoffs, tube life may be limited by the finite fatigue life of the bellows required to allow actuating tuners inside the vacuum. Tuners that operate outside the vacuum must still have adequate gear and bearing design if they are not to limit tube life; in particular, backlash may be a limit.

4.3 AMPLIFIER CHAIN TRANSMITTERS

It was the limitations of magnetrons that eventually pushed radars to use amplifier chain transmitters, which are more capable but also more complex. The key difference is that the transmitter signal is generated at low level, as precisely as desired, and is amplified all the way from there to the required peak power level. As shown in Figs. 15.44 and 15.45, the change in the system block diagram is small, just the direction of two arrows and the change from oscillator to amplifier for the high-power RF source; but there is a *huge* difference in the hardware required to implement the amplifier chain system, including many stages of RF amplification, each with its own power supplies, modulator, and controls; and *all* these stages must be stable to achieve good system MTI performance (Chap. 15).

Oscillator versus Amplifier. Amplifier chain systems can readily achieve full coherence from pulse to pulse and can provide all the features that pulsed oscillator systems (usually magnetrons) cannot provide: coded pulses, true frequency agility, and combining and arraying. The price is higher system complexity and cost. Thus, "oscillator versus amplifier" is one of the basic choices that must be made early in radar system design. Some of the factors entering into this choice are given below.

Accuracy and Stability of Carrier Frequency. In an oscillator-type transmitter, the RF power tube determines its own operating frequency, as opposed to having it determined by a separate low-power stable oscillator. The frequency may thus be affected by tube warmup drift, temperature drift, pushing, pulling, tuner backlash, and calibration error. In an amplifier chain type of transmitter, the frequency accuracy is essentially equal to that of its low-level stable crystal (or other) oscillator. Furthermore, the frequency of the amplifier chain can be changed instantaneously by electronic switching among several oscillators, at a rate faster than that of any mechanical tuner.

Coherence. An amplifier chain system can generate its LO (local oscillator) and coho [coherent intermediate-frequency (IF) oscillator] signals with precision, whereas an oscillator-type transmitter requires manual tuning or an automatic frequency control (AFC) servosystem to tune the LO to the correct frequency. Since an oscillator-type transmitter starts each pulse at an arbitrary phase angle with respect to the coho and LO, coho locking must be provided; in an amplifier system, coho locking is inherent in the signal generation process. Furthermore, since phase coherence can be maintained over a train of pulses in an amplifier-type transmitter, second-time-around clutter can also be canceled, whereas in an oscillator-type system, second-time-around clutter will be noise-modulated by the random starting phase of the oscillator tube. Amplifier chains also allow full coherence, in which the PRF, IF, and RF frequencies are all locked together; this is sometimes necessary to keep PRF harmonics out of IF doppler bands.

Instabilities. As discussed in Secs. 4.6 and 15.11, different kinds of instabilities are associated with a pulsed oscillator system and a pulsed amplifier chain. For the oscillator, pulse-to-pulse *frequency* stability depends on HVPS ripple, and intrapulse *frequency* changes depend on modulator droop and ringing. Tolerable limits are shown in Table 15.4, but these limits may be loosened if coho locking is based on an effective average of the transmitter frequency during the pulse length. For an amplifier chain, pulse-to-pulse *phase* stability depends on HVPS ripple, and intrapulse *phase* variations depend on droop and ringing; tolerable limits are also shown in Table 15.4.

An interesting compromise is also feasible: if a locked coho is used with an amplifier chain, then pulse-to-pulse phase variations in the chain are not significant (except on second-time-around clutter). This technique is particularly convenient when a CFA power booster is added to an existing pulsed oscillator MTI radar system; simply by changing the point at which the RF sample is taken for locking the existing coho, the added CFA is not required to have tight pulse-to-pulse phase stability.

A digital equivalent of the locked coho has also been used. The phase of the transmitter is simply measured on each pulse, and the proper correction is made on the received signals in the signal processor. Like the locked coho, this technique is not effective on second-time-around targets.

Amplifier Chains: Special Considerations. The decision to use an amplifier chain, most often for coherence and agility, introduces many complications, some of which are noted here.

Timing. Because modulator rise times differ, triggers to each amplifier stage must usually be separately adjusted to provide proper synchronization without excessive wasted beam energy. In CFA chains, allowance must also be made for the pulse-width shrinkage that occurs because of the necessary overlap of RF drive, as noted in Sec. 4.4.

Isolation. Each intermediate stage of a chain must see proper load match even if the following stage has high VSWR input, as in a typical broadband klystron, or even if it has significant reverse-directed power coming back from it, as is the case with CFAs. This reverse-directed power results from mismatch at the CFA output that sends power back through the low-loss structure of the CFA. For example, a load with 1.5:1 VSWR reflects power 14 dB down. At certain frequencies, this reflected power will combine with reflections inside the tube and may typically return to the input of the CFA at a power level only 8 dB down from full output power. This amount of reverse-directed power is 2 dB *greater* than the RF input power arriving at that point even if the CFA has only 10 dB of gain. Although this does not seem to interfere with normal CFA operation, it does require an isolator at the CFA input with 16 dB isolation, in this case, just to bring the VSWR seen by the previous stage down to 1.5:1.

Matching. RF tubes used in amplifier chains are often more "fussy" about the match they see than oscillator tubes. Because good isolators are now generally available, improved amplifier ratings are sometimes available if the tube is guaranteed to see a good match, such as 1.1:1. Furthermore, CFAs and traveling-wave tubes (TWTs) generally require that the match they see be controlled over a much wider range than the specified operating frequency band to ensure that the amplifier tube will remain stable.

Signal-to-Noise Ratio. The noise power output of an amplifier tube may be significant. When several tubes are connected as a chain, the output signal-to-noise ratio cannot be better than that of the worst stage. For this reason the input stage, especially, must be checked to see if it has an adequately low noise figure; otherwise, it may prevent the entire chain from achieving a satisfactory signal-to-noise ratio. For example, a low-level TWT with 0.5-mW RF signal input and 35 dB noise figure will limit signal-to-noise ratio of the amplifier chain to 74 dB in a 1-MHz bandwidth. Conventional CFAs have higher noise levels than linear-beam tubes, and their signal-to-noise ratio is typically only 55 dB in a 1-MHz bandwidth; the low-noise CFA, however, can be 70 dB or better (Sec. 4.4).

Leveling. In a multistage chain of linear-beam tubes, the performance of each tube depends in part on the performance of the tubes preceding it. In particular, power flatness (constant power output across the frequency band) requires careful specification of flatness for each stage in the presence of a suitable allowance of nonflatness of the stage preceding it. For example, the *saturated gain* of a tube may be constant across the band, and yet the power output may vary considerably across the band with constant RF drive. Saturated gain is measured by varying the drive at each frequency until the point of maximum power output is found; at that point, saturated gain is the ratio of RF power output divided by RF power input. Unless the saturated power output is constant over the band, the saturated gain bears little relationship to power flatness across the band with constant RF drive. Nor does flat small-signal gain indicate power flatness at large-signal conditions. Therefore, it is usually best to specify that the tube be tested in a way that will ensure proper performance in the system, including adequate tolerances on the RF drive.

Naturally, the transmitter gain and leveling plan must cover all losses and tolerances of components between the stages as well as the tube tolerances. It is also feasible to consider passive frequency-shaping networks to compensate for known deviations from flatness in the RF tube characteristics.

In CFA chains, leveling is far simpler because excess drive power is harmless (it just feeds through and adds to the output),[15] and it is only necessary to ensure that there is always adequate drive power.

Stability Budgets. In a multistage chain, each stage must have better stability than the overall requirement on the transmitter, since the contributions of all stages may add. They may add randomly or directly, or in certain cases they may be arranged to cancel, depending on the nature and source of the instabilities. Normally it is necessary to subdivide the transmitter stability requirement into several smaller numbers that are then allocated to each stage according to *degree of difficulty.* Such *stability budgets* are usually required for pulse-to-pulse variations, for intrapulse variations, and sometimes for phase linearity. Jitter is usually dependent primarily on a single stage and is therefore usually not budgeted among stages.

RF Leakage. A typical amplifier chain may have 90 dB of gain at the transmitter frequency in one shielded room or one location. In order to keep the chain from oscillating, leakage from the output of the chain back to its input must clearly be at least 90 dB down. However, a more stringent requirement is that RF leakage into the input stage of the chain must be kept below the desired level of MTI *purity* with respect to the signal level at that point, since the leakage path might conceivably be modulated by fan blades, cabinet vibration, etc. The leakage feedback will also affect pulse compression sidelobe levels. Since a typical level of purity desired for MTI or pulse compression might be 50 dB, this leads to an isolation requirement of 140 dB from chain output to input. Since typical waveguide joints and coaxial-cable connectors may have leakage levels of the order of −60 dB, 140 dB of isolation can be difficult. Other contributors to amplifier chain RF leakage problems often include collector seals on linear-beam tubes and cathode stems on CFAs. Successful amplifier chain design therefore requires conscious and careful control of RF leakage.

Reliability. The complexity of transmitter amplifier chains often makes it difficult to achieve the desired reliability. Solutions usually involve the use of redundant stages or a whole redundant chain, and many combinations of switching are feasible. Careful analysis and restraint are usually necessary; otherwise, the complexity and cost of fault monitoring and automatic switching very quickly grow out of bounds. Appropriate design for acceptable reliability involves trading off various serial and redundant transmitter chain and switching alternatives, but such system-reliability calculations are beyond the scope of this handbook.

RF Amplifiers. Successful amplifier chain transmitter design depends upon the availability of suitable RF amplifier devices or the feasibility of developing them. Since solid-state transmitters are covered in Chap. 5, we will limit this chapter to discussions of RF tubes for radar systems, as described in the next section.

4.4 RF AMPLIFIER TUBES

Until the mid-1970s, radar transmitters used only vacuum tubes of one kind or another for microwave power generation. The earliest systems all used magnetrons, as has been noted, and amplifier chain system development had to await the development of suitable high-power pulsed-amplifier tubes. Although many varieties were developed, the successful kinds were klystrons, TWTs, and CFAs. Triodes and tetrodes[2] have also been used in radars at frequencies below 600 MHz.

Klystrons and TWTs are called *linear-beam tubes* because the direction of the dc electric field that accelerates the electron beam coincides with the axis of the magnetic field that focuses and confines the beam. This is in contrast to *crossed-field tubes*, such as magnetrons and CFAs, in which the electric and magnetic fields are at right angles to each other.

Since there are a number of excellent references that describe the theory and operation of RF amplifier tubes,[2–4,16–18] this discussion will be limited primarily to system considerations in selecting and using microwave amplifier tubes in radar transmitters.

Crossed-Field Amplifiers (CFAs). High efficiency, small size, and relatively low-voltage operation make CFAs especially attractive for lightweight systems for transportable or airborne use, from UHF to K band. Having relatively low gain, CFAs are generally used only in the one or two highest-power stages of an amplifier chain, where they may offer an advantage in efficiency, operating voltage, size, and/or weight compared with linear-beam tubes. The output-stage CFA is usually preceded by a medium-power TWT that provides most of the chain gain. CFAs have also been used to boost the power output of previously existing radar systems.

The dominant types of CFAs are all reentrant, distributed emission

CFAs.[4,16–18] The high-gain CFA[19] was not developed until 1987, but it is very attractive, both because it requires less drive power and because the presence of RF drive at the cathode results in lower noise levels.

Backward-wave CFAs were developed first and were applied first (the amplitron).[15] In backward-wave devices, the voltage required for a given peak current is essentially proportional to frequency, but this can be accommodated by the inherent contant-power characteristic of a line-type modulator or by a hard-tube modulator operated in the constant-current region. The constant-current switch tube also helps to regulate CFA current against HVPS capacitor-bank-voltage droop. Forward-wave CFAs, which were developed later, operate at nearly constant voltage across their frequency band and can therefore be considered for *dc operation*, which requires only a control electrode (see below) instead of a full-power pulse modulator.

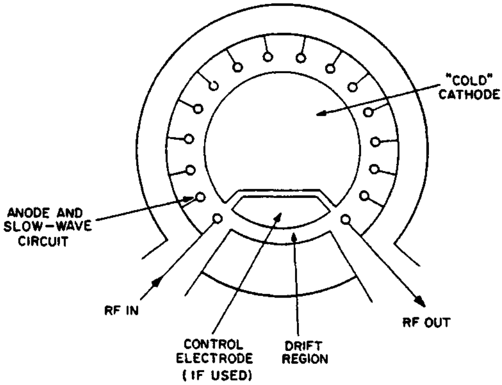

FIG. 4.6 Drift region and control electrode in a reentrant CFA.

Some CFAs have cold cathodes and are started by applying RF drive. The RF drive power must be applied in time to permit the tube to start drawing current before the cathode voltage pulse overshoots the proper operating voltage. However, even when there is a drift region in the CFA, as shown in Fig. 4.6, the tube will not stop when RF drive is removed; the reentrant electrons still carry enough energy that secondary emission from the cathode is maintained, and the tube will oscillate near a band edge or generate broadband noise until the cathode voltage pulse ends. In addition, once operation has been started by RF drive, back bombardment heats the cathode, and on following pulses the cathode current may start from thermionic emission even before RF drive is applied. Since this would also produce noise output, it is customary to make the RF drive pulse straddle the modulator voltage pulse to prevent this. Allowance must be made for the resulting pulse-width shrinkage in an amplifier chain with one or more CFAs. The output pulse will also have "pedestals" owing to feedthrough of the wider RF drive pulse length, as shown in Fig. 4.7.

A control electrode[20,21] usually consists of a segment of the cathode structure in the drift region, as shown in Fig. 4.6. The control electrode is pulsed positive

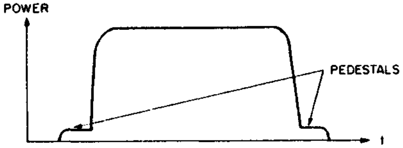

FIG. 4.7 Pedestals on a CFA RF output pulse.

(with respect to the cathode) at the end of the RF pulse to collect the electrons passing through the drift region and thereby make the tube turn off even though high voltage is still applied.[22] Turnoff control electrodes in CFAs thus make possible dc operation, which eliminates the high-power modulator. In dc operation, the high voltage is continuously present between anode and cathode, and the current is turned on by applying RF drive and turned off by pulsing the control electrode. To prevent the tube from starting without RF drive, the cathode must be kept cool enough to prevent thermionic emission. The control electrode requires only a short, medium-power pulse, typically one-third of the anode voltage and one-third of the anode peak current. The greatly reduced modulator requirements for dc operation make it practical to use more complex pulse coding. However, some energy is dissipated on the control electrode each time it is pulsed, and since it is an insulated electrode, it is difficult to cool. Control-electrode heating can therefore be a limitation on the maximum PRF that may be used.

In practice, dc operation has seldom been used[23] because it requires a much larger capacitor bank to limit droop (as opposed to using a switch tube in the constant-current mode) and because an arc in a dc-operated CFA requires crowbarring (Sec. 4.9), which interrupts operation for a few seconds instead of only for a single pulse; it has not been possible to make CFAs arc-free. Problems have also occurred as a result of adjacent radars injecting enough RF energy into the system antenna and back into the transmitter to turn on a dc-operated CFA at the wrong times.

The low insertion loss of CFAs from RF input to RF output without modulator voltage applied permits convenient programming of CFA amplifier chain power output in steps.[24] For example, in an amplifier chain transmitter with two CFAs preceded by a TWT, three power-output levels can be selected simply by choosing which modulators to pulse. Power programming, also called *feedthrough operation*, is especially useful in 3D radar applications, since it permits conserving average power by reducing the peak power output at high scan angles.

The low insertion loss of a CFA also allows power reflected at the output to be passed back through the tube to its input; in many cases the reflected output power coming back out of the input may even exceed the incoming drive power. A properly rated isolator[3,25] is thus a necessity between stages of a CFA chain.

Certain additional problems long identified with magnetron operation are also common to operation of CFAs. For details, see paragraphs on sparking, moding, noise rings, spurious RF output, and RF leakage, discussed under "Common Problems" in magnetrons (Sec. 4.2). One difference is that because RF drive is present during the voltage rise time, many (but not all) cathode-pulsed CFAs allow a much faster voltage rate of rise than magnetrons. For the same reason (i.e., RF drive is already present) there is little starting-time delay in the desired CFA operating mode; but the π-mode oscillation has a finite starting time and will produce little energy if the voltage passes quickly enough through the range in which it can occur. In a dc-operated CFA, the π-mode oscillation should not occur at all because the cathode voltage is at full value all the time.

Klystrons. The multicavity klystron has always been known for its high-gain and high-power capability. However, its bandwidth during the 1950s tended to be 1 percent or less, with wider ranges being covered by mechanical tuning of the cavities; *gang tuning* (tuning all cavities at once in response to rotation of a single tuning knob or motor drive) is often used. Although a tradeoff between klystron gain and bandwidth was always known to be feasible, the stagger tuning of a klystron is far more complex than that of an IF strip. The overall frequency response of a klystron contains intermediate gain products as well as the total product of the individual cavity responses; certain tuning combinations produce excessive harmonic output; and broadband small-signal gain does not ensure broadband saturated gain. Klystron bandwidth capability increases with power level[16] because the stronger beam provides heavier loading of the cavities.

Modern digital computers made it possible to determine improved cavity-tuning arrangements, and klystron bandwidth improved greatly; 8 percent bandwidth 3 dB down) has been obtained with fixed cavity settings, and even 11 percent in rare cases (Varian VA-812C). The achievement of this bandwidth in klystrons also depended partly on improvements in beam perveance, but, more important, it required progress in output-cavity design, because the *power bandwidth* can be no better than the ability of the output cavity alone to extract the energy from the beam, regardless of the gain or drive power available preceding it. Single-cavity output circuits are therefore replaced in broadband klystrons by double-tuned and triple-tuned cavities, sometimes called an *extended-interaction circuit*,[26,27] which uses more than one interaction gap to extract energy from the beam, as shown in Fig. 4.8. This technique of grouping cavities was later extended to the prior cavities as well, and by discovering that the cavities in each group need not be coupled to each other, the *clustered-cavity klystron*[28] has achieved as much as 20 percent bandwidth. Although more complex and expensive than a normal klystron, the clustered-cavity klystron is still less complex and costly than a comparable TWT or Twystron.

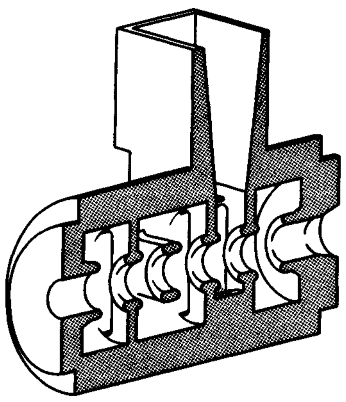

FIG. 4.8 Extended-interaction output circuit. *(From Ref. 26.)*

Traveling-Wave Tubes (TWTs). The low-power helix TWT is still the king of bandwidth. Because it has virtually constant phase velocity at all frequencies, the helix permits TWTs to have bandwidths in excess of an octave. However, the helix TWT has not been used in high-power radars because high power requires a high-voltage beam, and the resulting electron velocity is too fast to synchronize with the low velocity of the RF wave on a helix slow-wave circuit. The limit of helix tubes is about 10 kV and a peak RF power output of a few kilowatts. For higher power levels, other kinds of slow-wave circuits with a higher RF velocity must be used, and the bandpass characteristics of those circuits can lead to band-edge oscillation problems. Furthermore, both forward waves and backward waves may propagate on the RF structures, leading to the possibility of backward-wave oscillations. Depending on the circuit used, other kinds of oscillations can also occur. For

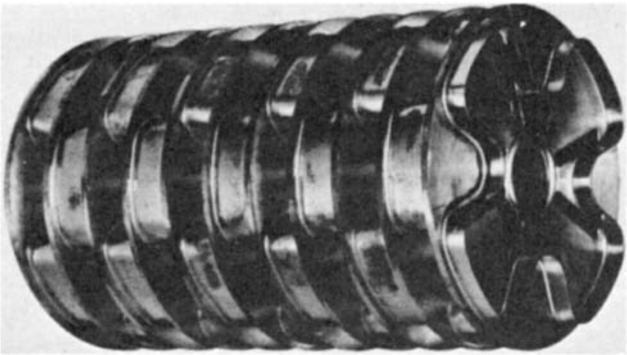

FIG. 4.9 Cloverleaf slow-wave circuit. *(Courtesy of Varian Associates.)*

these reasons, high-power TWT development lagged that of klystrons and is still more expensive. By 1963, however, Varian had produced multimegawatt pulsed TWTs using the cloverleaf circuit, as shown in Fig. 4.9,[29] a structure that can be made heavy and rugged enough to handle power comparable with that of klystrons.

Slow-wave structures for high-power TWTs include helix-derived structures (contrawound helix, or ring-bar circuit) and coupled-cavity circuits, of which the cloverleaf is one example, and the ladder network.[30] Below 100 kW, ring-bar circuits usually have broader bandwidth and higher efficiency than coupled-cavity circuits. Above 200 kW or even below that if average power is a limitation, coupled-cavity circuits dominate.[31]

If a TWT using a coupled-cavity circuit is cathode-pulsed, there is an instant during the rise and fall of voltage when the beam velocity becomes synchronous with the cutoff frequency (π mode) of the RF circuit, and the tube usually oscillates. These oscillations at the leading and trailing edges of the RF output pulse have a characteristic appearance that has given them the name *rabbit ears*, as shown in Fig. 4.10. Only in rare cases has it been possible to suppress these oscillations completely. However, since this particular oscillation depends on electron velocity, which in turn depends on beam voltage, the problem is avoided by the use of mod-anode or grid pulsing (described later in this section). In this case, it is only necessary to be sure not to let the modulator begin pulsing the beam current during turn-on of the HVPS until the voltage is safely above the oscillation range, which is typically somewhere between 60 and 80 percent of full operating voltage.

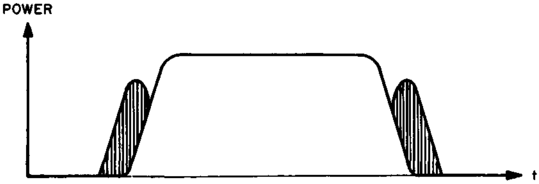

FIG. 4.10 Rabbit-ear oscillations on the envelope of the RF output from a cathode-pulsed TWT amplifier.

Discontinuities, called *severs*, are necessary in the slow-wave structure of high-power TWTs to prevent oscillation due to reflections at input and output of the structure. Although oscillation could also be prevented by distributing loss along the structure, this would result in lower efficiency, which is unattractive in high-power tubes. Typically, a sever is used for each 15 to 30 dB of tube gain. At each sever, the modulated beam carries the signal forward, while the power traveling in the slow-wave circuit at that point is dissipated in the sever loads; thus reverse-directed power is stopped at each sever. The sever loads may be placed external to the tube to reduce dissipation within the RF structure itself.

TWTs tend to be less efficient than klystrons because of the necessity for loading the structure for stability and because relatively high RF power is present in an appreciable fraction of the entire structure. One important technique for improving the efficiency of high-power TWTs is called *velocity tapering*. This technique consists of tapering the length of the last few circuit sections of the slow-wave circuit to take into account the slowing down of the beam as the energy is extracted from it. Velocity tapering permits extracting more of the energy from the beam and significantly improves the power-bandwidth performance of the tube.[31] Nevertheless, high-power TWTs generally show an appreciable falloff of power output toward the band edges, so that the rated bandwidth depends very much on how much power falloff can be tolerated by the system.

To improve the efficiency of TWTs (or klystrons), the use of depressed collectors[16,32] has been developed to a remarkably successful degree. The use of multiple collector sections at intermediate voltages allows catching each spent electron at a voltage near optimum. Up to 10 collector sections have been used in some communications tubes, but 3 sections, as shown in Fig. 4.11, are more typical for modern high-power TWTs for radar systems. The several different voltages needed for the depressed collectors add complexity to the HVPS, but fortunately these voltages need not be as well regulated as the main beam voltage.

Twystrons. In 1963 Varian assembled a hybrid tube consisting of klystron cavities in all but the output section, while a cloverleaf traveling-wave circuit was used for the output section. The purpose was to produce a more efficient version of the VA-125 broadband S-band TWT, based on the more effective beam-bunching action of the cavities. The result was not only slightly higher efficiency but also a significant improvement in bandwidth as a result of the flexibility in tuning of the cavities combined with the broad power-bandwidth capability of the TWT output section. To compensate for the inherent droop in gain of the TWT output section at the edges of the band, the klystron cavities were purposely tuned to boost the gain at those frequencies. Because it is part klystron and part TWT, Varian named the hybrid tube a Twystron.[33] A 3 dB bandwidth of 14 percent has been demonstrated in the VA-145, or a 1 dB bandwidth of 12 percent; 48 percent efficiency has been shown at midband with 41 dB gain. Although more complex and expensive than most klystrons, the Twystron appears capable of equally high power with broader bandwidth than all but perhaps the clustered-cavity klystron.

RF Tube Selection. Table 4.1 summarizes the main differences among the leading RF tube types. The factors that most often dominate in tube selection are cost, bandwidth, spurious noise level, control electrodes, gain, size, voltage, and availability (not shown in the table). Linear-beam tubes are quieter and higher-gain and can be grid-pulsed, but CFAs are smaller, lighter, lower-voltage, and less costly. Sometimes one of these factors is overwhelmingly important, and the transmitter designer is forced to accommodate all the less

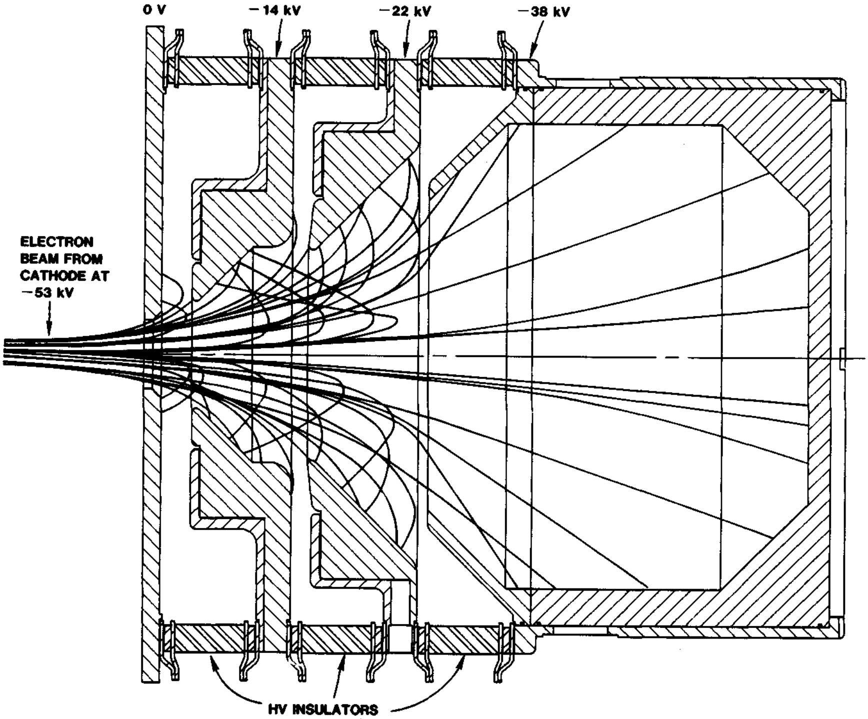

FIG. 4.11 Multiple depressed collectors. *(Courtesy of Hughes Aircraft Electron Dynamics Division.)*

significant disadvantages. Often, several choices are feasible, and tradeoffs are then considered among system cost, schedule, and performance. Further comments on Table 4.1 are given below.

Voltage. Voltage affects the size and cost of the HVPS and modulator as well as x-ray severity.

Gain. Gain strongly affects the number of stages and therefore the complexity (parts count, control, fault monitoring, and maintenance) required in an amplifier chain.

Bandwidth. The bandwidth listed here is the instantaneous bandwidth of the tube, i.e., without tuning adjustments. The tube bandwidth must be compatible with system requirements; in turn, system bandwidth tends to be based on available or presumed tube capabilities.

X-rays. X-rays affect transmitter weight because of the shielding required to protect personnel (and sensitive semiconductors).

Efficiency. This strongly affects transmitter weight, cost, and cooling requirements as well as prime power. The numbers shown do *not* include heater power, solenoid power, or cooling-system power, which may be significant.

Ion Pump. Residual outgassing in a microwave tube can spoil its vacuum and cause RF or dc breakdown. A Vac-Ion pump (trademark of Varian Associates) can be used to maintain a good vacuum, even during storage, and to indicate the quality of the vacuum. Most crossed-field tubes don't require ion pumps because they will pump themselves down when operated.

TABLE 4.1 High-Power Pulsed Amplifiers Compared for Same Frequency and Peak and Average Power Output

	Linear-beam tubes		Crossed-field tubes*	
	Klystron	TWT	Conventional	High-gain
Voltage	High voltage (1 MW requires approx. 90 kV)		Low voltage (1 MW requires approx. 40 kV)	
Gain	30–70 dB		8–15 dB	15–30 dB
Bandwidth	1–8%†	10–15%	10–15%	
X-rays	Severe, but lead is reliable		Not usually a problem	
Efficiency				
Basic	15–30%		35–45%	
With depressed collectors	40–60%		N.A.	
Ion pump	Required on large tubes		Self-pumping	
Weight	Higher		Lower	
Size	Larger		Smaller	
Cost	Medium	High	Medium	
Spurious noise‡	−90 dB		−55 dB	−70 dB
Spurious modes (typical)	None	π mode during rise and fall if cathode-pulsed; none if mod-anode- or grid-pulsed	π mode during rise and fall if cathode-pulsed; full-power noise output if turned on without RF drive	
Usable dynamic range	40–80 dB		A few decibels	
Control electrode	None, or mod-anode, or grid		None, or turnoff electrode	
Magnetic field	PPM up to 1 MW at S band; solenoid otherwise; barrel magnet rare (SLAC); none for ESFK		Permanent magnet	
Dynamic/static impedance	0.8		0.05–0.2	
Phase-modulation sensitivity	5–40° per 1% $\Delta E/E$		0.5–3.0° per 1% $\Delta I/I$	

*Distributed emission, reentrant, circular.
†Clustered-cavity klystron can achieve 10 to 15 percent bandwidth at higher cost.
‡In 1-MHz bandwidth.

Weight. The weights of the tubes alone are compared in Table 4.1; however, the solenoid required for high-power linear-beam tubes and their higher voltages usually make linear-beam-tube transmitters considerably heavier than CFA transmitters.

Size. The same comments apply as noted under "Weight."

Cost. The costs listed here refer only to tube costs. Also see comments under "Control Electrodes," below. The comments listed apply roughly to both development costs and unit costs.

Spurious Noise. This has become a more significant factor as radar bands become more crowded, receiver sensitivities increase, and electromagnetic compatibility (EMC) receives more attention. Spurious noise should be considered in four parts:

1. *Harmonics:* Both linear-beam tubes and CFAs produce harmonic power output of typically −25 dB (with respect to fundamental power output) at the sec-

ond harmonic, −30 dB at the third harmonic, and considerably less at higher harmonics. Although these figures vary greatly from one tube design to another, there is no strong difference between linear-beam tubes and CFAs in general. If harmonic power output is a problem, excellent high-power microwave filters are practical.

2. *Adjacent-band spurious noise:* Problems of this type may occur from adjacent modes in CFAs or in TWTs, typically appearing a few percent above (in forward-wave tubes) or below (in backward-wave tubes) the desired operating band. The problem may be severe in cathode-pulsed tubes but is avoided in tubes pulsed by a control electrode (dc-operated CFA, or mod-anode or gridded TWT). If present, adjacent-band spurious noise is usually easy to filter out unless it is too close to the desired operating band.

3. *In-band spurious noise:* This is the factor noted in Table 4.1, since it is most serious to system operation and usually cannot be filtered out. In-band spurious noise may interfere with other systems or may prevent achieving desired MTI cancellation or pulse compression sidelobe levels in the tube's own system. In-band spurious noise also sets a limit on the spectrum improvement that may be obtained by pulse shaping (Sec. 4.7). In-band spurious noise may also be degraded by the source of RF drive (Sec. 4.3).

4. *Interpulse noise:* Unlike the above three factors, interpulse noise is the noise produced by an RF tube when it is supposed to be completely off; that is, between pulses. Noise generated at this time is of concern because, in almost all radar system configurations, this noise will feed directly into the radar receiver and may either produce false targets or mask real targets. In cathode-pulsed tubes, the high voltage is removed from the RF tube between pulses, and no interference with receiver operation is normally encountered unless there is excessive modulator fall time or backswing, which can produce *noise rings* (Sec. 4.2). With dc-operated CFAs or with mod-anode or gridded linear-beam tubes, the high voltage remains on the tube between pulses, and serious noise may be generated if even a small amount of beam current is allowed to flow through the tube. Since all dc-operated CFAs use cold cathodes, no current can flow until RF drive is applied. With linear-beam tubes, beam current must be well enough cut off to keep noise output (and amplified input signals) small enough. Despite the nearly 200 dB between typical RF peak power output and typical receiver noise levels, most RF tubes readily meet the interpulse-noise requirements. Problems occurred mostly with older-style intercepting-grid linear-beam tubes because the hot grid may emit and produce residual beam current even if cathode current is cut off.

Spurious Modes. The spurious modes listed in Table 4.1 are the ones most commonly present. In some cases tubes have been made in which these modes are fully suppressed, whereas in poorly designed tubes other modes may also appear, such as band-edge oscillations, harmonic oscillations, etc.

Usable Dynamic Range. Dynamic range and linearity may be of importance for pulse shaping, as discussed in Sec. 4.7.

Control Electrodes. These determine the type of modulator required, which in turn affects transmitter size, weight, complexity, and cost. Control electrodes avoid the need for a full-power cathode-pulse modulator. A *mod-anode* (modulating anode) can be used in any linear-beam tube; it acts like a control grid with a mu of 1 and is inexpensive and reliable. A high-mu grid is also feasible for all but the very highest power linear-beam tubes, and it greatly simplifies the modulator requirements; but it raises the cost and may lower reliability and life of the tube.

Magnetic Field. Except for a few electrostatically focused klystrons,[34,35] all magnetrons, CFAs, klystrons, and TWTs require a magnetic field to control the path of the electron beam. Virtually all CFAs use permanent magnets. Periodic permanent magnet (PPM) focusing is used on all but very high power linear-beam tubes, which still require solenoids. Use of a solenoid affects transmitter size, weight, efficiency, cost, servicing, and tube protection.

Dynamic Impedance. This indicates how rapidly the tube current changes for a given change in applied voltage (also see Table 4.2). The significance of this factor depends on the type of modulator used, or it may affect the HVPS capacitor bank size required for a given permissible power droop during the pulse length (Sec. 4.8).

Phase-Modulation Sensitivity. This indicates how hard the transmitter designer must work to ensure that system phase-stability requirements will be met (Sec. 4.6). Large as the difference may seem between linear-beam tubes and CFAs in this characteristic, modulation sensitivity is seldom a dominant factor in RF tube selection. However, it does enter into the size, weight, and cost tradeoffs by its effect on HVPS filter size or on modulator complexity.

Historically, it has always been feasible to obtain the extremely low ripple levels desired for MTI systems, limited only by inherent noise levels (including jitter and starting-time noise) in the tubes. For pulse compression systems, the necessary freedom from ringing during the pulse length has been fairly easy to achieve with hard-tube modulators and difficult to achieve with line-type modulators, with either linear-beam tubes or CFAs.[36]

Life. Linear-beam tubes and CFAs have both shown the feasibility of long life (over 40,000 h in some cases), but both have also shown very short life when the wrong tube-design compromises were made, when development problems remained, or when tubes were misapplied or carelessly handled in the field. Attainment of very long life, in the region of 10,000 h or more, requires judicious selection of power ratings, conservative cathode-current density, and conscientious counseling of the marriage between tube and transmitter.

RF Tube Power Capabilities. The peak power capabilities of RF tubes have progressed sufficiently far that the limitation has become breakdown in practical waveguide systems, even with 20 lb/in^2 of SF_6 in the waveguide. Therefore, since the early 1960s there has been a tendency for radar systems to employ increased duty cycle, by the use of techniques such as pulse compression, to achieve higher average power without a further increase in peak power. Although in many cases a single RF tube can produce so much average power that even pure-copper waveguide requires water cooling, the limit in system average power may still be the RF tube. Furthermore, asking for the ultimate power capability in one RF tube has a high risk of leading to an unsuccessful development program or to an unreliable tube even if the development is "successful." From a reliability standpoint as well, multiple smaller tubes are often preferable to a single very large tube. Therefore, it has become quite common for high-power radar systems to use more than a single RF tube, as described in the next section.