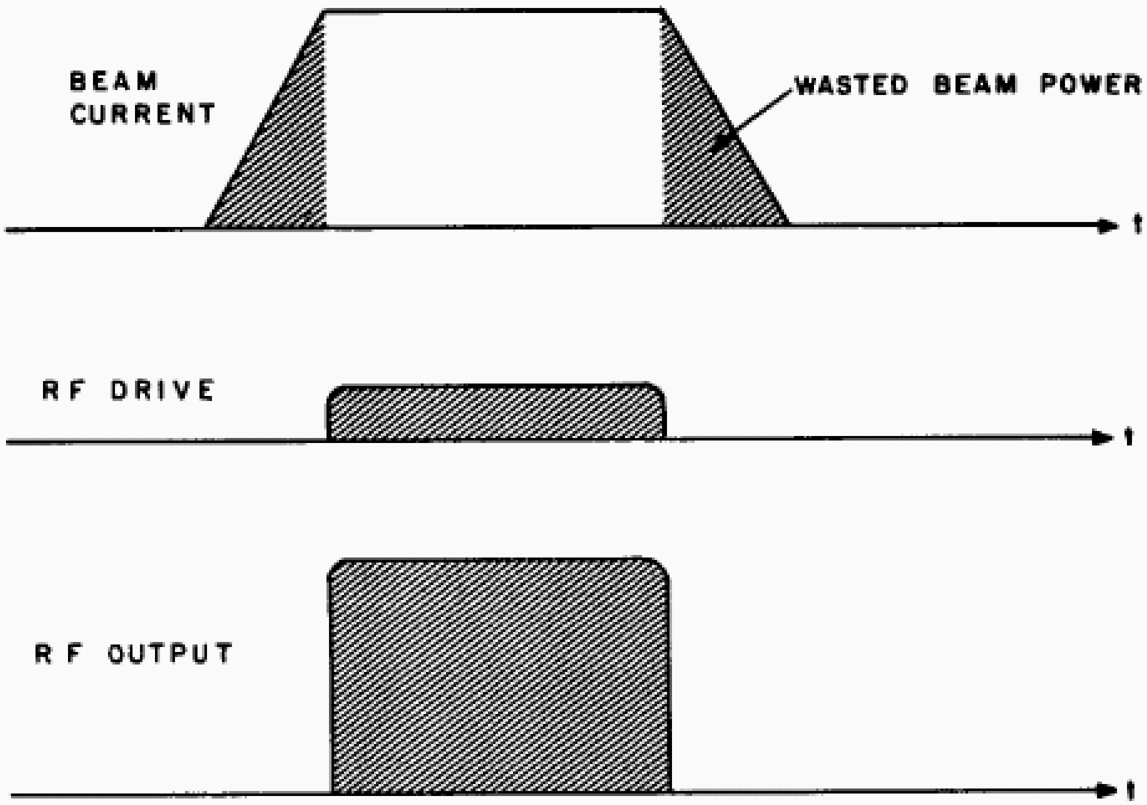


FIG. 4.14 Use of gated RF drive to avoid phase distortion. The figure also shows wasted beam power during modulator rise and fall times.

Pulses with Shaped Edges. A simpler and yet effective approach to spectrum improvement is to shape only the rise and fall of a rectangular pulse.[57] This attenuates the spectrum at frequencies far from f_0, while the flat-topped center portion of the pulse retains high transmitter efficiency for most of the pulse duration. Since a rectangular pulse has the best transmitter efficiency but the widest spectrum, whereas a gaussian pulse has the narrowest spectrum but very poor transmitter efficiency, the fraction of the pulse length to be used for the shaped rise and fall is a crucial decision.

Although the improvement attainable in practice is limited by phase modulation in the transmitter during the rise and fall,[54,56,58] significant improvements can be obtained. In a linear-beam-tube transmitter with properly shaped RF drive, for example, the spectrum width at 60 dB down can usually be narrowed by about an order of magnitude at a cost of about 1 dB in transmitter efficiency.

In practice, most amplifier chain radar systems, whether tube or solid-state, now use at least some shaping of the edges of the transmitted RF pulse to reduce RF spectrum width. This is usually done simply by slowing the rise and fall times of the exciter signal to the transmitter; this has generally been adequate to satisfy MIL-STD-469 and related system requirements.

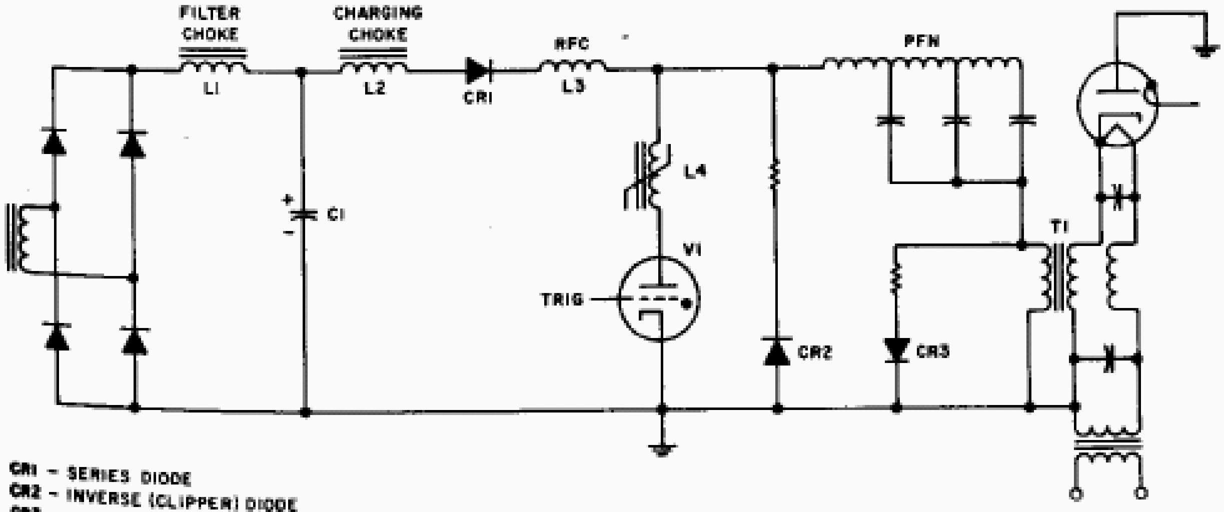
4.8 PULSE MODULATORS

Since pulse-modulator design is well covered in existing literature,[59–61] this section will mainly summarize and compare available modulator techniques. The type of modulator required is usually determined by the available type of RF tube. A grid pulser, for example, is the smallest, easiest, and least expensive type of modulator, but it can only be used if the RF tube has a grid. Although grids have become more common, a grid may still not be feasible in a very high power RF tube. On the other hand, several types of modulators may be suitable for a given application; Table 4.3 compares some of the performance advantages and disadvantages of various modulator techniques. The final choice is then based on tradeoffs among cost, size, weight, efficiency, and life. The conclusions vary greatly as a function of system requirements and the type of RF tube to be pulsed, as proved by the wide variety of modulators in use.

Line-Type Modulators. The classic line-type modulator is shown in Fig. 4.15. In this type of modulator, the switching device *V*1 (thyratron, ignitron, silicon controlled rectifier, reverse-switching rectifier,[62] or spark gap) merely initiates and carries the discharge of the pulse-forming network (PFN); the actual shape and duration of the pulse are determined entirely by the PFN and other passive circuit elements. The pulse ends when the passive elements have discharged sufficiently that current in the switch stops and allows the switch to recover its voltage hold-off capability.

The self-terminating nature of the pulse discharge is what permits the use of simple switching devices (fully on or fully off only), but this characteristic is also the greatest weakness of line-type modulators. The switching device merely times the pulse discharge and has no control on the pulse shape. Although the PRF can be varied if a series diode is used in the resonant-charging circuit,[59] pulse length can only be changed by switching the connections to multiple PFNs or PFN sections, which requires high-voltage switches. For similar reasons, the trailing edge of the pulse is usually not sharp, since it depends on the energy stored in multiple reactive elements all going to zero at the same time. Furthermore, a well-matched condition is difficult to achieve into nonlinear loads such as RF tubes and all their stray circuit impedances. Achieving the desired pulse shape into very nonlinear loads such as magnetrons often requires despiking or damping circuits.[9,59]

Heater power (if required) for the RF tube load is usually supplied either by a low-capacity high-voltage-insulated heater transformer or by a bifilar secondary winding on the pulse transformer, as shown in Fig. 4.15.



CR1 - SERIES DIODE
CR2 - INVERSE (CLIPPER) DIODE
CR3 - BACKSWING DAMPER DIODE
RFC - RF CHOKE TO ISOLATE STRAY CAPACITIES
L4 - MAGNETIC ASSIST (IF USED)
T1 - PULSE TRANSFORMER (SHOWN WITH BIFILAR SECONDARY)

FIG. 4.15 Line-type modulator.

TABLE 4.3 Comparison of Modulators

Modulator		Fig.	Flexibility		Pulse-length capability		Pulse flatness	Crowbar required		Modulator voltage level
			Duty cycle	Mixed pulse lengths	Long	Short		Load arc	Switch arc	
Line type	Thyratron SCR	15	Limited by charging circuit	No	Large PFN	Good	Ripples	No		Medium Low
Magnetic modulator		. . .	Limited by reset and charging time	No	Large C's and PFN	Good	Ripples	No		Low
Hybrid SCR magnetic modulator		. . .	Limited by reset and charging time	No	Large C's and PFN	Good	Ripples	No		Low
Active switch	Series switch	16*a*	No limit	Yes	Excellent; large capacitor bank	Good	Good	Maybe	Yes	High
	Capacitor-coupled	16*b*	Limited	Yes	Large coupling capacitor	Good	Good	Maybe	Yes	High
	Transformer-coupled	16*c*	Limited	Yes	Difficult; XF gets big; large capacitor bank	Good	Fair	Maybe	Yes	Medium-high
	Mod-anode	17	No limit	Yes	Excellent; large capacitor bank	OK, but efficiency low	Excellent	Yes	Yes	High
	Grid	. . .	No limit	Yes	Excellent; large capacitor bank	Excellent	Excellent	Yes	. . .	Low

Operation of a line-type modulator into a mismatched load results in residual energy in the PFN at the end of the desired pulse length. If the load is lower than match (i.e., if the load impedance is lower than the PFN impedance as seen through the pulse transformer), the energy remains as a voltage of reverse polarity on the PFN. Within limits, this allows additional time for the switch device to recover, but an inverse clipper diode (*CR*2 in Fig. 4.15) is required to discharge this energy so that the charging voltage on the next pulse will not be affected.

A well-designed clipper circuit[59,63,64] will prevent the charging voltage from rising more than a few percent on the next charging cycle even when the load arcs and presents a short circuit to the modulator. Observation of the peak charging voltage[65] while a grounding stick is used to simulate arcing of the RF tube will quickly show how effective a particular clipper circuit may be, and all line-type modulators should be subjected to this test. Crossed-field tubes must be allowed to arc occasionally without tripping off the modulator, especially during "burn-in," and modern modulators are usually designed not to trip off unless the arcing continues excessively.

When a line-type modulator is operated into a load impedance higher than match, a train of pulses of exponentially decaying amplitude is theoretically expected, leading to concern that the thyratron will not deionize before the next charging cycle begins. This indeed occurs on a pure resistive load and results in "hangfire" of the thyratron and trip-off of the modulator. However, the presence of the pulse transformer in typical line-type-modulator circuits ensures that the modulator can operate properly into a load higher than match. The buildup of magnetizing current in the pulse transformer continues to discharge the PFN until its voltage reverses (perhaps after several pulse lengths), just as if the load were lower than match.

Since a line-type modulator ordinarily runs at or near match, moderate variations in load impedance can be analyzed on the basis that constant power will be delivered by the modulator. This is true as long as the PFN charging voltage is constant, which depends on having an effective clipper circuit. Similarly, a 1 percent increase in peak charging voltage will produce a 2 percent increase in power delivered to the load, regardless of its dynamic impedance (Table 4.2).

Various line-type-modulator arrangements using more than one PFN are feasible in order to produce an output pulse at a different impedance level than that switched by the thyratron.[59,66] This may offer advantages in certain cases, but in general these techniques increase the PFN cost and make it harder to achieve good pulse shape. Since in these cases the voltage on the PFN has both polarities during normal operation, it is awkward or impossible to achieve effective clipper-circuit action. The result is that most multiple-network modulators tend to have multiple postpulses (extraneous pulse outputs following the desired pulse output) due to multiple internal reflections of the residual energy in the several PFNs. For these reasons multiple-PFN modulators are relatively uncommon in radar usage.

Throughout the history of line-type modulators, high-power applications have grown faster than switching devices, so two or more of the largest devices have often been used in series or parallel to handle higher peak or average power.[61,67]

Active-Switch Modulators. There is such a variety of active-switch pulse modulators that it is useful to categorize them as cathode pulsers, mod-anode pulsers, and grid pulsers. Cathode pulsers must control the full beam power of the RF tube, either directly or through a coupling circuit. Mod-anode pulsers must usually provide a voltage swing equal to the full beam voltage of the tube, but the current required is only that needed to charge and discharge the circuit capacitances at the beginning and end of the pulse, since a mod-anode usually draws very little current during the pulse. Pulsers for gridded RF tubes perform the same kind of task as mod-anode pulsers, but since the term *grid* is used here to describe a high-mu control electrode, the voltage swing required from a grid pulser is far smaller and permits the use of lower-voltage components and techniques.

Before semiconductors became available, these types of modulators were all called *hard-tube modulators* because they used vacuum tubes exclusively. Active-switch modulators require switching devices that can be both turned on and turned off at will, since, unlike the line-type modulator, the switching device controls both the beginning and the end of the pulse. In active-switch modulators, the pulse is terminated when only a fraction of the stored energy available in the HVPS or modulator has been delivered to the load.

Transistors and gate-turnoff silicon-controlled rectifiers (SCRs) are the only semiconductors inherently capable of being turned off at will, but their power-handling capabilities are much lower than those of conventional SCRs. Therefore, because interest in using semiconductors for high power has been so great, special commutating circuits have been developed to make SCRs turn off at a desired time by means of other SCRs. Although the same techniques could be applied to hydrogen thyratrons and other switching devices normally limited to line-type modulators, it has not been done, probably because a multiplicity of hot cathodes is less palatable than a multiplicity of semiconductor devices.

In general, active-switch modulators provide great flexibility in pulse length and PRF, including mixed pulse lengths and bursts of pulses, since the pulse length is generated by low-level circuits. Maximum-pulse-length capability, within some allowable droop limit, is determined by the size of the energy storage capacitor used (and pulse transformer, if used). Since the energy stored in a capacitor is $CE^2/2$, a 5 percent voltage-droop limit (for example) means that the capacitor must store 10 times the energy delivered to the load in a single pulse. In high-power transmitters with long pulse lengths, the capacitor becomes very large, requiring series and/or parallel combinations of many capacitors, since the maximum practical energy in a single capacitor case is a few thousand joules. The collection of capacitors is then usually known as a capacitor bank (where the joules are stored), and such banks are reasonably common in the range of 10,000 to 1 million J. For example, a transmitter delivering 10 MW of peak power to an RF tube for 100 μs (1000 J per pulse) requires at least a 10,000-J capacitor bank to limit droop to 4 percent, which will produce about a 13 percent droop on the RF output power of a linear-beam tube (unless droop compensation is used, as discussed below). The problem is about 4 times as severe for CFAs because of their low dynamic impedance (Table 4.2).

Special circuits can be used to reduce the effective droop for a given capacitor bank size or to reduce the capacitor bank size for a given allowable droop. Droop can be eliminated (although some ripple is likely to be added) by adding inductors to make the capacitor bank appear as a low-impedance PFN,[68] but this works well only for a fixed pulse length. Droop compensation is less critical and can be accomplished by inserting a parallel *RL* network in series between the capacitor bank and the pulsed load.[69] The drop across the *RL* network is highest at the start of the pulse and gradually decreases during the pulse, which tends to cancel the droop; but some energy is lost in the *RL* network. As an example, a 5 percent droop can be reduced to 2 percent with an efficiency loss of 2 percent.

In general, active-switch modulators are capable of excellent pulse shape if careful attention is paid to stray circuit inductances and capacitances, since there is no lumped-section PFN to limit rise time and to introduce ripple during the pulse length.

Like line-type modulators, active-switch modulators must be designed to tolerate occasional load arcing without damage. Since the RF tube is connected directly to the energy storage capacitor bank in the case of dc-operated CFAs or in the case of a linear-beam tube using mod-anode or grid pulsing, a crowbar (Sec. 4.9) is required to protect the tube from being damaged by the discharge of all that energy when a load arc occurs. With a cathode pulser, the switching device should ordinarily be able to interrupt the load arc current, and firing the crowbar should not be necessary unless the switching device itself arcs.

Cathode Pulsers. The basic types of active-switch cathode pulsers are shown in Fig. 4.16. The triode shown represents any suitable active switch, either a hard tube or a string of solid-state devices, and the linear-beam tube shown as the load represents any cathode-pulsed RF tube, whether crossed-field or linear-beam and whether oscillator or amplifier. Table 4.3 provides a comparison of the features of cathode pulsers.

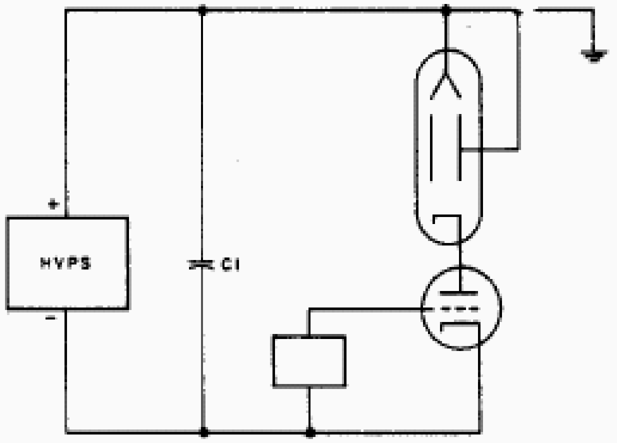
There are two basic types of cathode pulsers. Most often, the switching device is driven hard enough to bring its voltage as low as possible during the pulse; the device is said to be *bottomed*. This approach minimizes switching-device dissipation and maximizes efficiency, but variations in power supply voltage due to rectification ripple, line-voltage variations, or energy-storage-capacitor droop are passed directly to the load. The alternative is to operate the switching device as a *constant-current* device by limiting its drive signal. The effects of capacitor-bank-voltage droop and of power-supply-voltage variations on the load are then reduced by $(Rp + R_L)/R_L$, where Rp is the dynamic resistance of the device and R_L is the dynamic resistance of the load (Table 4.2).

Tetrode switch tubes are better suited to constant-current service than triodes because of their higher plate resistance. However, in constant-current operation, any fluctuations in grid drive affect load current directly, whereas if the switch tube is bottomed, variations in grid drive have relatively little effect. In constant-current operation, the grid drive may also be programmed to provide even better droop reduction than is provided by constant grid drive; for example, a rising *ramp* on the grid drive can be adjusted to compensate fully for the droop on the energy storage capacitor during the pulse.[68]

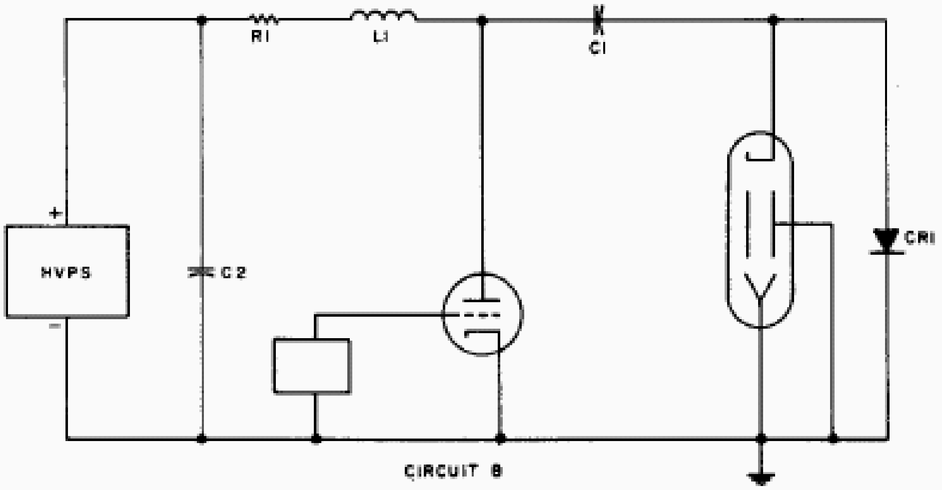
As the power ratings of metal-oxide-semiconductor field-effect transistors (MOSFETs) have grown, series strings of these devices have become attractive for use in active-switch modulators at increasingly high power levels, both as bottomed switches and as constant-current switches.[70]

Mod-Anode Pulsers. A basic modulating-anode pulser, sometimes called a floating-deck modulator, is shown in Fig. 4.17.[71–73] The klystron shown represents any linear-beam tube having a mod-anode, and the triodes shown represent any suitable active-switch device. During the pulse the ON tube holds the mod-anode near ground potential to turn on the klystron, and between pulses $R3$ holds the mod-anode negatively biased with respect to the klystron cathode to keep the klystron beam current cut off. The ON tube carries significant current only during the leading edge of the pulse when it is charging up the mod-anode stray capacitance C_s (including all associated stray capacitances, such as that of the ON deck), and the OFF tube similarly carries significant current only to discharge C_s at the end of the pulse. The OFF tube may be thought of as an end-of-pulse *tailbiter*, which is vital in this case since the load on the modulator is primarily capacitive.

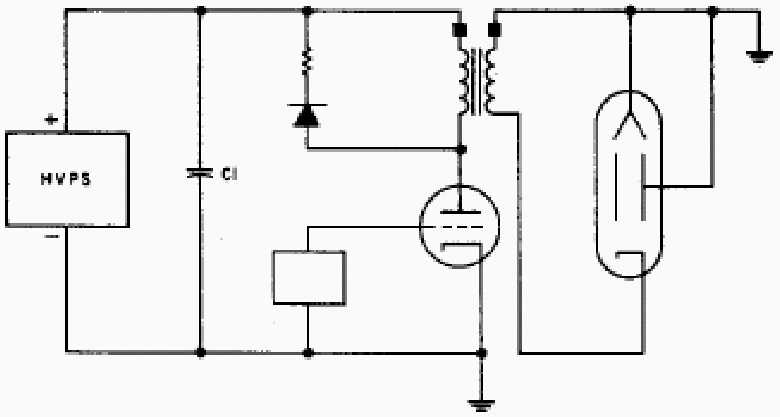
Extremely good pulse flatness during the pulse can be obtained with mod-anode pulsers because the klystron is directly across the capacitor bank and because variations in grid drive to the ON tube during the pulse can readily be



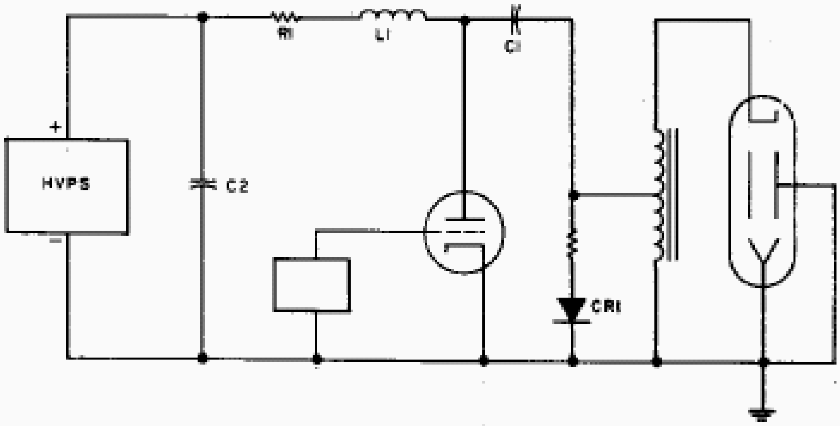
CIRCUIT A



CIRCUIT B



CIRCUIT C



CIRCUIT D

FIG. 4.16 Active-switch cathode pulsers: circuit *A*, direct-coupled; circuit *B*, capacitor-coupled; circuit *C*, transformer-coupled; circuit *D*, capacitor- and transformer-coupled.

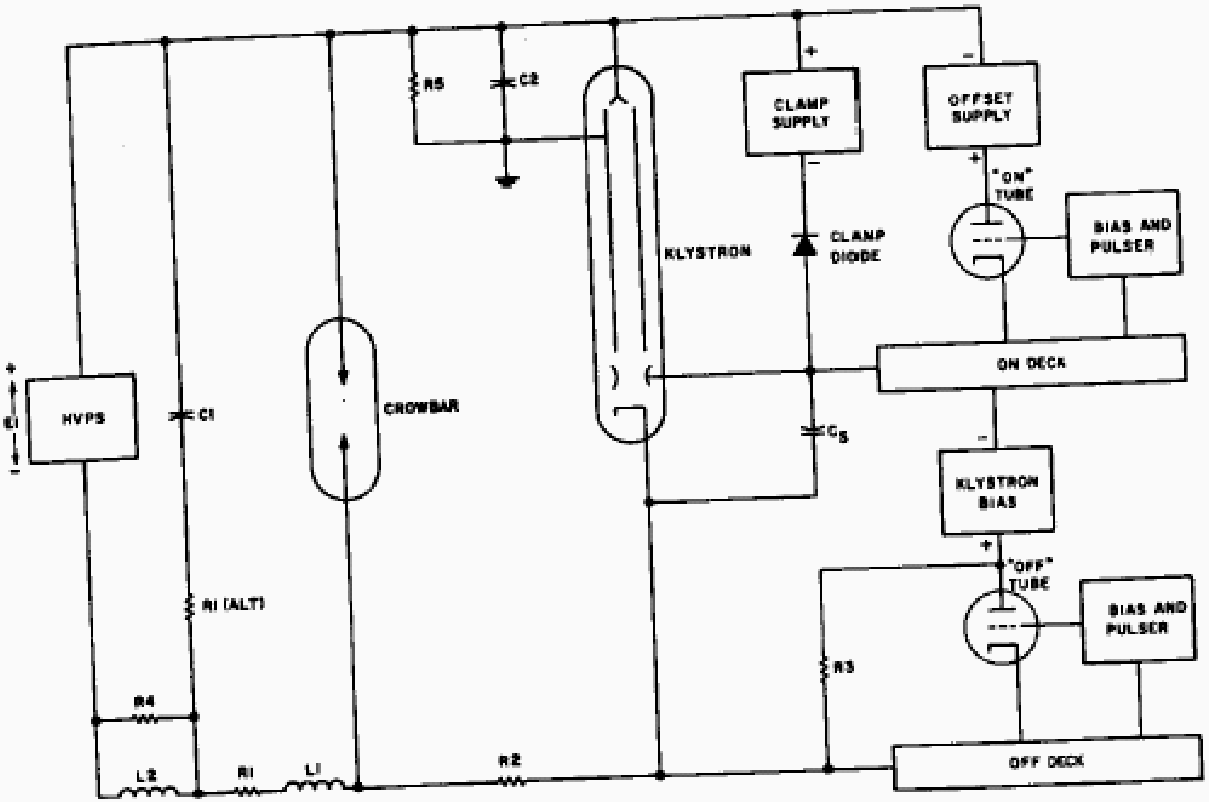


FIG. 4.17 Modulating-anode pulser: direct-coupled.

clamped to produce a flat-topped pulse. Except for capacitor bank size, there is no limit on maximum pulse length, but with very short pulses efficiency drops because of the finite time and energy it takes to turn the mod anode on and off. The ON and OFF tubes can be considerably smaller than a switch tube for cathode-pulsing the same klystron, since they carry less current and carry it only briefly. However, power and triggers must be coupled to two decks floating at high voltage, one of which is at the dc power supply voltage $E1$ and one of which pulses up and down with the mod anode. Since the dissipation in each switch tube is essentially $C_s\,(E1)^2/2$ times the PRF, it is important to minimize C_s, especially if the PRF is high.

Grid Pulsers. When the RF tube has a high-mu grid, the pulse required for it becomes quite small, comparable with the pulse required for the grid of a switch tube in other kinds of hard-tube modulators, and will not be described here. All the types of modulators previously mentioned may be considered, except that the voltage excursion required for grid pulsing is much less than full beam voltage. Because stray-capacity charging losses are reduced by the square of the mu, grid modulators can more readily handle high-PRF and/or burst-mode operation of radars and are often called on to do so.

4.9 HIGH-VOLTAGE CROWBARS, REGULATORS, AND POWER SUPPLIES

Providing the power needed by RF tubes and their pulse modulators involves a number of considerations that are peculiar to radar transmitters, as described in the following subsections.