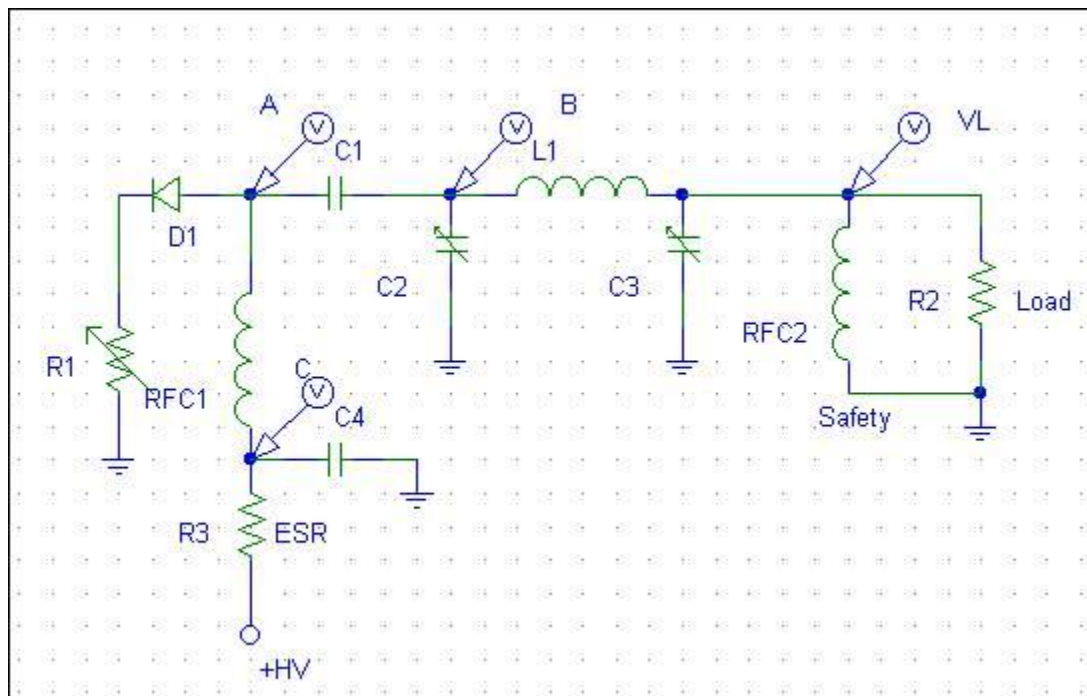


# How Vacuum Tubes in Linear Circuits Work

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## How the PA Tube Converts DC anode voltage to Radio Frequency Power

A typical vacuum tube radio-frequency amplifier has a high voltage power source. This power source supplies the energy for the RF output power. The vacuum tube acts like a

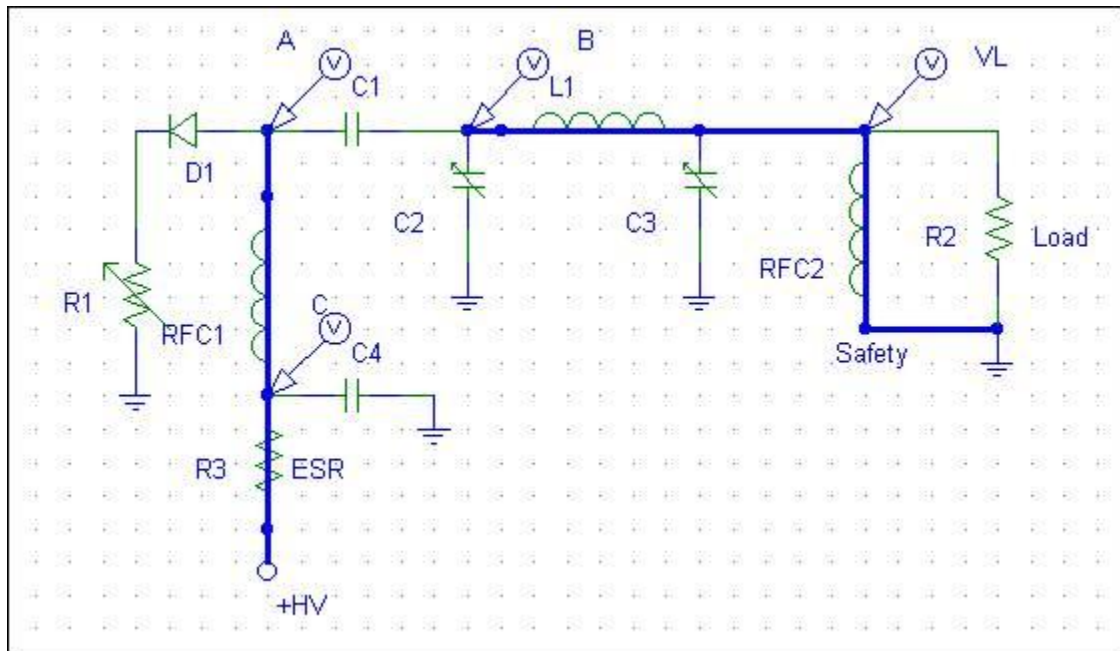


non-linear variable resistance in series with a diode. The electrical equivalent of the anode and output system

is: R1 represents the time-varying anode-to-cathode resistance of the output device. As grid-cathode and anode-cathode voltage changes, R1's value changes. D1 represents the directional characteristics of the tube anode-to-cathode current path. D1 is always "on" when the voltage at point "A" is more positive than ground. D1 would also behave as a current limiter, the current always having to be something less than the saturated emission current of the cathode. The only exception to this is if the tube shorts or arcs internally. Let's examine how this circuit converts DC to RF power. We will assume +HV is 3000 volts. In the initial state, C1 has been charged through the following DC path: Hopefully the designer was smart enough to include RFC2, to prevent charging or discharging C1 into the load, which might be a sensitive piece of gear (or the operator)! The voltage across C1 is the anode-to-ground voltage at A. Everything past A, at B and VL, is zero volts in the resting state. This is because of the low-dc resistance of RFC2 and the nearly infinite resistance (and dc impedance) of

capacitor C1. RFC1, the plate choke, establishes a fixed or static magnetic field, the intensity of which is set by the quiescent or steady-state tube idle current flowing through anode-to-cathode resistance R1. As a positive-going grid-to-cathode RF voltage decreases anode-to-cathode resistance R1, the magnetic flux stored in the inductance of RFC1 tries to hold supply current steady. RFC1 reacts to the current change by increasing voltage across its terminals. Energy stored in the electric field of C1 tries to hold the voltage steady, and it sources any additional current the tube (R1) requires. The anode, in effect, "tugs" or pulls point A towards ground. The initial peak current can be quite high, limited only by plate-to-cathode resistance, because C1 has a low-reactance path to ground through C2. The tank inductor L1 also builds up a magnetic field, as plate tuning capacitor C2 develops a charge and gradually increasing voltage. This voltage increase comes from the current flowing through C2 and C1 back to the tube. On the initial RF cycle, the voltages hardly change before the grid is moving back negative. At a time interval equal to  $1/(4F)$  (where F is the RF frequency), the positive grid voltage has peaked. The grid begins to swing negative (or less positive) with respect to the cathode. Anode-cathode resistance (R1) decreases in step with decreasing grid-cathode voltage. The collapsing field in L1 (and to a much lesser extent RFC1) tries to hold anode current to the same value, and in doing so the collapsing magnetic fields supply a small amount of additional anode voltage. Since there

is no forced upward swing (the tube cannot source anything), tank components are left



to pull the small voltage change back up to the original anode voltage and slightly beyond. L1 (and to a lesser extent RFC1) will actually pull the anode voltage higher by an amount nearly equal to the amount the tube pulled the anode voltage

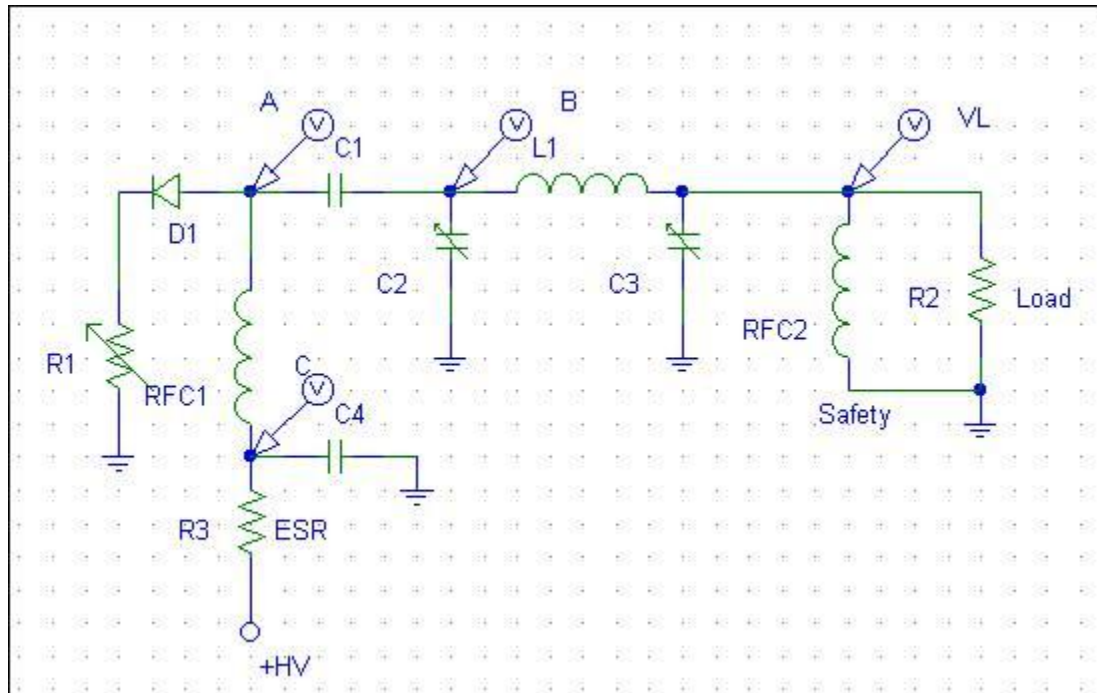
downwards, *or more. The actual amount the tank pulls this voltage higher than +HV depends on the amount of energy transferred to the load compared to energy stored in the tank system!* This is VERY important in understanding where arcs come from! Some switching power supplies, many ignition coils used in automobiles, and the flyback systems in television receivers use this type of "flyback effect" voltage to step up voltages to very high levels without use of transformer action. This cycle repeats over and over, and assuming the tank system at C2, L1, and C3 is resonant, the voltage at point A increases in swing while the peak current through R1 (the tube) is gradually reduced. Eventually, *in a fully loaded amplifier*, equilibrium is reached. In a *properly tuned amplifier* running at maximum available power, equilibrium occurs when point "A" swings up and down an amount just under twice the anode DC voltage. Consider a class AB 3-500Z using a 3000-volt supply. When the amplifier is tuned into the load properly at full rated power, and driven to full power, anode voltage will swing between 5500 volts maximum and 500 volts minimum at point A. This would be a *total anode voltage swing of 5000 volts*. Peak anode current in continuous carrier operation would typically be 1.12 amperes, with a minimum R1 value of 446 ohms. This is typical of continuous CW power out of 750 watts with a single 3-500Z tube with a 190-degree conduction angle running at 400mA anode current. Let's assume (we actually CAN have this condition, if the amplifier and exciter relays are not sequenced correctly) we have an envelope that rises instantly. At the peak of first positive grid-cathode cycle, the anode resistance would drop to someplace well under 400 ohms (anode resistance is non-linear with anode voltage, and is lower with higher anode voltages). The saturated anode current could reach 7.5 amperes in the 3-500Z, if tube grid-cathode bias permits. (Emission in a directly heated thoriated-tungsten tube is typically in the range of 50-100mA per watt of heater power, large transmitting tubes being at the upper end of that range. A full-emission 3-500Z has a saturated emission current of about 7.5 amperes.) If we have infinitely fast envelope rise and fall times from the exciter, amplifier RF-envelope rise and fall times are determined by the operating Q of the tank system. C2/L1/C3 dominate the high frequency energy storage. RFC1 and C1, being larger values, dominate lower-frequency energy storage, while stored energy in the power supply dominates long-term energy demands. The voltage across C2, upon initial application of RF drive, is a rapidly expanding sine wave. It reaches maximum steady-state swing many dozens or hundreds of RF cycles later than the initial tube excitation (and decaying in a similar fashion). The peak voltage across C2 is equal to the peak anode voltage swing, and the peak-to-peak voltage is slightly less than twice the HV supply voltage in NORMAL operation. The voltage across C3 is a function of the load resistance, and power delivered to the load.

## Incorrect Loading or Load

We know the tank circuit stores energy. We now understand the conversion process where DC is converted to AC (or RF) power. We also must understand **energy must be transferred out of the tank at a rate equal to or exceeding the rate at which it is supplied by the downward “pull” of the tube.** If we do not remove energy at a sufficient rate, voltages and currents increase until a new point of equilibrium is reached. Voltage at point “A” can actually swing well beyond twice +HV on upward excursions, and below zero volts (becoming negative) on downward excursions.

The maximum voltage with a load or drive fault can be tremendously higher under the fault condition than typical properly operating tank working voltages (when energy is being removed at the proper rate). If we do not remove energy from the tank at the same

rate the power supply is supplying energy, the voltage in the tank will increase until something absorbs that energy!

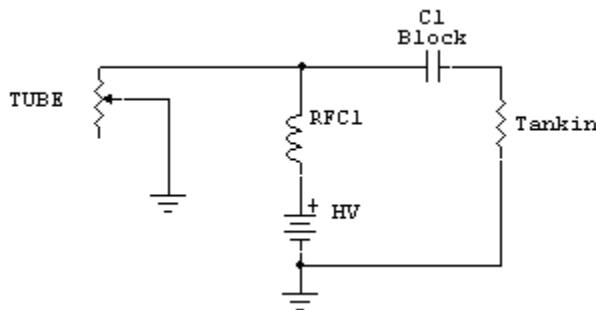


We have the same basic tank system as discussed earlier, but *with light loading compared to drive level* the tank is pulled down very hard by the tube. Minimum Rp is reached early in the cycle, before the tank voltage reaches it’s minimum swing. This is easy to do, since the tube only pulls the system down and the tank stores the energy of that downward tug. As the plate voltage swings below zero (negative) from the tank energy, the tube is already cutting off. Nothing clamps or prevents point A from going

negative. D1 effectively takes the tube out of the circuit. By the time the tank reaches its minimum, the tube's grid-cathode voltage is already on its way positive. The tank free wheels positive, and can overshoot the +HV supply by several times the supply voltage. If loading is light enough and Q is high enough, this continues until the energy stored in the tank reaches equilibrium with energy transferred to the load, or a component fails and the arc dampens the tanks gyrations. See the practical [demonstration page](#) for a real working model with waveforms!

### Proper Plate Load Impedance or Operating Impedance of an RF Amplifier

Since the anode-to-cathode resistance of the tube varies over the RF cycle, how do we establish the plate resistance of the tube? It all goes back to energy transfer. We must extract the same energy available from the power supply power drawn by the time-varying tube resistance, less any dissipation in the tube or loss in the tank components. Otherwise the anode voltage swing will not be in equilibrium, voltage swing will continue to build until something eventually extracts the energy at the same rate as it is applied. If we try to extract too much power to the load compared to the



optimum value, the output device current will increase. The tube path looks like this: The tank circuit transforms the load impedance of the antenna system or dummy load up to a new value. This resistance appears at C1, and is coupled through C1 to the tube and power supply junction. This is the resistance value we are actually calculating when we plan the

plate resistance,  $R_p$ .

This resistance has to match the optimum  $E/I$  of the desired RF frequency appearing at the anode of the tube. Let's consider the fundamental frequency only in a typical class AB amplifier operating near the class B end of the operating point. Let's assume we have 3000 volts of high voltage, and the tube performs best swinging down from 3000 volts to 500 volts. This is 2500 volts of peak anode voltage swing, and the flyback effect causes the anode to reach 3,000 (B+ value) + 2,500 (downward swing) = 5,500 volts on peak. Our vacuum tube has a peak dc anode voltage of 5,500 volts in **NORMAL** linear operation. If you develop an antenna system problem or have a bad lightning arrestor or relay, the peak voltage could be several times that amount.

If we think about this, all tubes should be tested to withstand at least twice the maximum dc anode voltage, and preferably more. This is a noteworthy point because test data from various Chinese manufacturers has indicated they test tubes at less than the rated dc supply voltage.

They should actually be testing and gettering tubes to withstand significantly more than twice the highest expected dc supply voltage. The old Eimac 3-500Z's, rated at 4,000 volts supply voltage, used to test to over 12,000 volts of anode-to-grid breakdown voltage. They virtually never arced when new.

I've seen test data from Chinese 572B's where the tubes were tested for arcing and failure at 1,500 volts dc anode voltage. Even an 811A should not be tested that low.

To be reliable an 811A tube should hold off nearly 5 kV with minimal leakage and no sign of arcing. A 572B should hold off over 8,000 volts.

With the 3-500Z example, we might have a useful RF output power of 800 watts with the anode swinging 2500 volts peak (5000 volts p-p), or about 1700 volts RMS at the fundamental. There are harmonics involved, so to do this right we would have to use a Fourier (harmonic waveform) analysis of the waveform, and there is just such an analysis that was developed for vacuum tubes called a Chaffee analysis, but for casual use we can use approximations. The typical rule of thumb for tubes with a 15% minimum plate voltage is we multiply indicated anode current by 1.6, and use the supply voltage.  $E_p / (I_p * 1.6) = R_p$ . Using this example we have  $3,000 / (.4 * 1.6) = 4,688$  ohms. Now let's look at another rough method. We know the swing is about 2500 volts, so RMS is about .7 times that.  $1750^2 / 750 = 4,083$  ohms. Using a Chaffee analysis the optimum load resistance comes out to 4500 ohms. The error in approximations is in not allowing for harmonic content.

## Tank Q

We often get far too worried about tank circuit Q. There really is very little change in efficiency as Q moves from a minimum of  $(\text{SQRT } R_p / R_l) + 1$ . If we had a 4500 ohm optimum anode load resistance ( $R_p$ ) and a minimum load resistance of 25 ohms, we would want a tank Q of at least  $\text{SQRT } 4500 / 25 = 13.4 + 1 = 14.4$ . A typical HF tank circuit, even with modest sized components and such a large impedance ratio, only has approximately 4 % power loss. If we doubled the Q, tank loss would only be 8 %. Lower impedance ratio tanks have even less loss and are less worrisome. Most of the power

loss is in the conduction angle of the tube, not tank Q. It is certainly not in a blocking capacitor, would would overheat and disintegrate if it had more than a tiny fraction of just one percent loss.

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